Biomechanical Analysis of Femoral Tunnel Pull-out Angles for Anterior Cruciate Ligament Reconstruction With Bioabsorbable and Metal Interference Screws

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Background: Fixation strength of metal and bioabsorbable interference screws has not been evaluated while varying the anterior cruciate ligament graft tension angle.

Hypothesis: There is no difference in fixation strength between 2 types of interference screws for anterior cruciate ligament graft fixation while the graft tension angle is varied relative to the femoral tunnel.

Study Design: Controlled laboratory study.

Methods: Forty-eight anterior cruciate ligament reconstructions were performed using immature porcine femurs stripped of soft tissue and doubled-over porcine flexor digitorum profundus tendon grafts. Specimens were randomized to bioabsorbable or titanium interference screw fixation. Specimens were randomized to one of three pull angles (0°, 30°, 60°) representing loading at different knee flexion angles (n = 8/group). Reconstructed ligaments were tensioned to 10 N followed by 200 loading cycles between 10 and 150 N and a final failure test. Construct elongation (mm) at 100 and 200 cycles and failure load (N) were analyzed using a 2-way analysis of variance ($P < .05$).

Results: Screw material interacted significantly with graft tension angle, as the bioabsorbable screw specimens demonstrated significantly greater fixation strength when tensioned at greater angles. Specimens fixed with bioabsorbable screws showed significantly less elongation at both 100 and 200 cycles and significantly greater failure load compared with titanium screws.

Conclusion: Bioabsorbable interference screws acutely have increased fixation strength compared with titanium interference screws for anterior cruciate ligament grafts loaded at greater tension angles.

Clinical Relevance: The strength of anterior cruciate ligament reconstruction fixation increases with increasing divergence between the tension angle and femoral tunnel, a condition seen when the knee approaches full extension.

Keywords: anterior cruciate ligament; reconstruction; knee flexion angle; biomechanical stability

Studies have shown that the long-term success of anterior cruciate ligament (ACL) reconstruction is strongly correlated with the strength and stability of ACL graft fixation at the femoral and tibial tunnels.[6,13,14,18,19] To evaluate the strength and stability of ACL fixation with various fixation devices and techniques, previous authors evaluated the pull-out strength of the soft tissue graft at the femoral tunnel and tibial tunnel attachments.[1,2,9] In these studies, the angle of pull relative to the femoral tunnel was usually set directly in line with the bone tunnel, a condition that is only achieved in vivo with the knee in hyperflexion.[1,2,6,7,9,15,32] However, in clinical practice, evaluation of the ACL reconstruction is conducted with tests (such as the Lachman and the anterior drawer) that assess strength and stability at various knee flexion angles.[16,31] In addition, the rehabilitation process is conducted

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with weightbearing activities over positions of relative knee extension.[3-5,12,24,30] These practices could change the interpretation of construct strength and may affect a surgeon's choice of femoral fixation hardware.

Pavlik et al[27] investigated ACL press-fit fixation using bone–patellar tendon grafts at pull-out angles ranging from 0° to 60° to simulate normal clinical conditions. That study showed variability in pull-out resistance of ACL grafts at different angles, because it was reported that ultimate tensile strength increased with the angle of pull on the ACL graft. Other studies have compared the effectiveness of bioabsorbable interference screws to metal interference screws in ACL graft fixation and found no significant difference between the 2 screw materials for pullout when subjected to pull forces directly in line with the femoral tunnel.[13,18,32]

No previous study has compared interference screw materials for ACL graft fixation under different angles of pull relative to the femoral tunnel. Because the knee is in a position at or near extension much of the time, it is important to directly evaluate and quantify the biomechanical stability of ACL reconstruction as a function of load angle using both metal and bioabsorbable interference screw fixation.

MATERIALS AND METHODS

Forty-eight knees from mature LWD (Landrace, Large White, Duroc) pigs (Animal Technologies, Tyler, Tex) weighing approximately 100 kg were dissected of all soft tissues. Each femur was disarticulated and its shaft transected 20 cm from the intercondylar notch, isolating the distal femur.[1,17-19] The cruciate ligament remnants were removed with a rongeur. Flexor digitorum profundus tendons were harvested from porcine hindquarters to be used as ACL grafts.[20-23,34] The tendons were prepared with a number 2 Ethibond whipstitch at either end and doubled over, giving cross-sectional areas between 7 and 9 mm.[18,20,22,23]

Femoral tunnel preparation was done with standard ACL reconstruction instrumentation (Stryker Endoscopy, San Jose, Calif). The distal femur was secured in a stationary vise. The over-the-top ACL femoral guide was placed at a position that corresponded to 6 to 7 mm anterior (depending on graft size) to the posterior femoral wall of the intercondylar notch. Additionally, to reproduce the native ACL femoral footprint, the guide was lateralized to the 10:30-o'clock position for right femurs and 1:30-o'clock position for left femurs, where 12:00 o'clock represented the direct vertical position. A Beath pin was then advanced through the native ACL footprint, exiting the anterior femoral cortex proximally at 45º. This angle was selected to prevent drilling into the femoral diaphyseal cavity. Exact reproduction of the native ACL insertion angle was unnecessary because the angles under investigation in this study were varied in the sagittal plane and based off a guide pin placed in the cannulated interference screw. Once the Beath pin was placed, the femoral tunnel was drilled over the Beath pin to a length of 35 mm. The selection of reamer size depended on graft size, where whole number diameter grafts required a same size reamer and non–whole number diameter grafts a half millimeter larger. For example, an 8.5-mm graft diameter

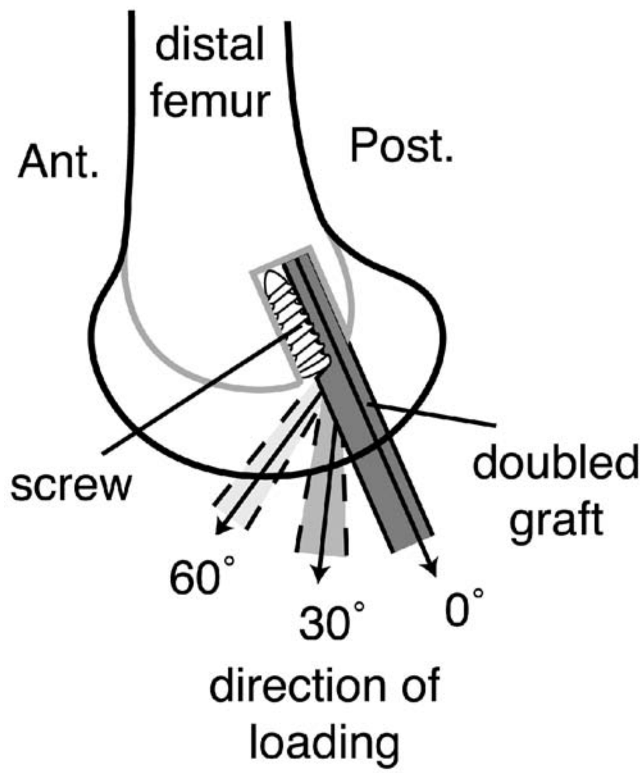

Figure 1. Schematic of varying angular position for loading the ACL reconstruction.

would require the use of a 9-mm reamer. Grafts were then loaded onto the Beath pin and pulled into the femoral tunnel. The screwdriver tip without a screw was advanced anteriorly into the tunnel adjacent to the graft at the 11:00-o'clock position to create a track for the interference screw. We chose an 11:00-o'clock position for screw placement because clinically this is the most appropriate location to avoid graft windup. Graft windup is related to the direction that the screw turns to advance the screw (ie, clockwise). By placing the screw to the left of the graft, we prevented, and prevent in the clinical situation, the graft from rolling under and then around the screw, thus weakening the graft and affecting its biomechanical evaluation.

The porcine femurs were randomly assigned to 1 of 2 screw-material groups. The different sized ACL grafts were randomly allocated between these groups. Graft fixation for the first group (metal screw group) relied on a titanium interference screw with a diameter 1 mm smaller than the predrilled bone tunnel. The second group (bioabsorbable screw group) used a poly-L-lactic acid (PLLA) interference screw (Bioscrew, Stryker Endoscopy, San Jose, Calif) that was also 1 mm smaller than the predrilled bone tunnel.

Porcine femurs from each group were then randomly assigned to 1 of 3 loading directions (n = 8 specimens per test group) simulating a postoperative early rehabilitation protocol. Grafts were positioned at 0º, 30º, and 60º of flexion relative to the bone tunnel (Figure 1). These loading angles were measured using a guide pin placed in the cannulated

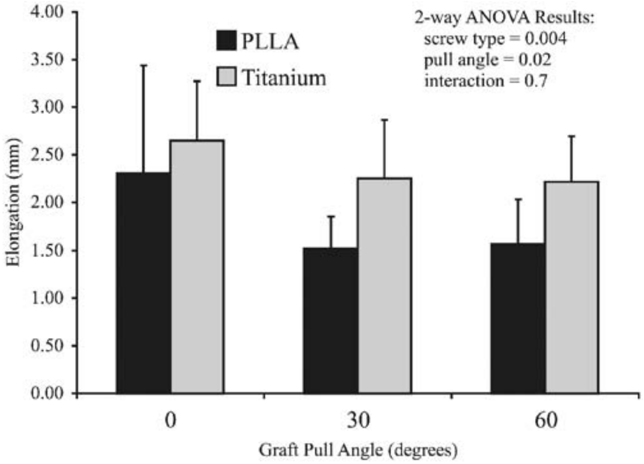

Figure 2. Magnitude of construct elongation after 100 cycles of loading. PLLA, poly-L-lactic acid; ANOVA, analysis of variance.

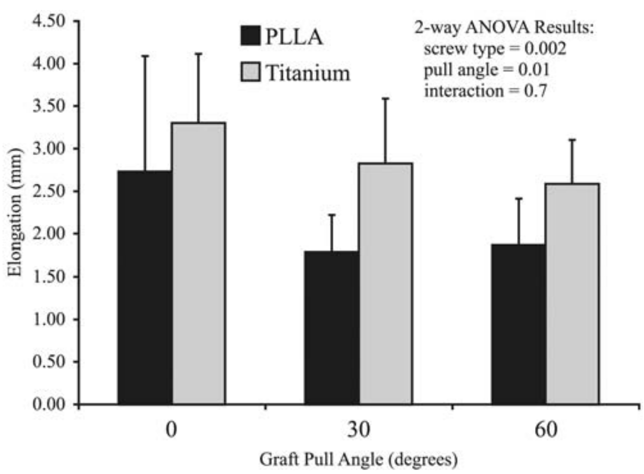

Figure 3. Magnitude of construct elongation after 200 cycles of loading. PLLA, poly-L-lactic acid; ANOVA, analysis of variance.

interference screw as a reference line. Considering a postoperative evaluation with lateral radiographs of 10 patients who had been treated by endoscopic ACL reconstruction, we estimated that the line of the femoral tunnel relative to the line of the tibial tunnel was approximately 60º with the knee in full extension.

Each femur was mounted on a biaxial servohydraulic materials testing machine (858 Mini-Bionix, MTS Inc, Eden Prairie, Minn) in one of the 3 loading directions. The trailing edges of the ACL graft were secured in soft tissue clamps. All grafts were pretensioned to 10 N for 2 minutes.[20] After pretensioning, all constructs were loaded between 10 and 150 N[11] at 0.25 Hz for 200 cycles. These parameters were chosen because in previous studies, graft displacement in cyclic loading tests was shown to occur primarily before 200 cycles.[1,18] After cyclic testing, constructs were then loaded to failure at 1 mm/s. Construct elongation (mm) at cycles 100 and 200 and failure load (N) were compared with a 2-way

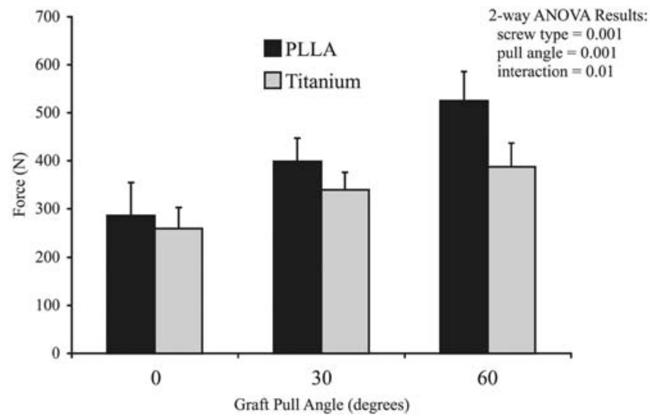

Figure 4. Failure load from failure testing after cyclic testing. PLLA, poly-L-lactic acid; ANOVA, analysis of variance.

analysis of variance ($P < .05$) (dependent variables: pull angle and screw type) using a Tukey's post hoc correction test for multiple comparisons. All data are presented as mean ± SD.

RESULTS

Grafts were visually examined during testing to ensure that there was no tissue slippage from within the clamps. There were significant differences in elongation after 100 load cycles related to both graft load angle ($P = .02$) and screw material ($P = .004$), although the interaction term was not significant (Figure 2). Specimens with resorbable screws (0° = 2.3 ± 1.1 mm; 30° = 1.5 ± 0.3 mm; 60° = 1.6 ± 0.5 mm) demonstrated lower elongation values than specimens fixed with metal screws (0° = 2.6 ± 0.6 mm; 30° = 2.3 ± 0.6 mm; 60° = 2.2 ± 0.5 mm). Individual comparisons did not yield significant differences.

Elongation after 200 load cycles demonstrated trends that were similar to those for the 100-cycle elongation phenomena. The differences in elongation after 200 load cycles were significant for both different graft load angles ($P = .01$) and screw materials ($P = .002$), whereas the interaction term was not significant (Figure 3). Specimens with resorbable screws (0° = 2.7 ± 1.4 mm; 30° = 1.8 ± 0.4 mm; 60° = 1.9 ± 0.5 mm) demonstrated lower elongation values than those fixed with metal screws (0° = 3.3 ± 0.8 mm; 30° = 2.8 ± 0.8 mm; 60° = 2.6 ± 0.5 mm). Individual comparisons did not yield significant differences.

The differences in failure load related to both graft load angle ($P = .001$) and screw material were significant ($P = .001$) (Figure 4). In this particular test, the interaction term was also significant ($P = .01$). Specimens with resorbable screws (0° = 285.7 ± 69.1 N; 30° = 398.5 ± 48.7 N; 60° = 524.7 ± 61.1 N) demonstrated higher failure loads than specimens fixed with metal screws (0° = 260.3 ± 42.0 N; 30° = 339.1 ± 36.6 N; 60° = 387.1 ± 49.3 N). As evidenced by the significant interaction term and the increasing difference between failure loads at subsequent knee flexion angles, it appears that the resorbable screw exerts a greater stabilizing affect as

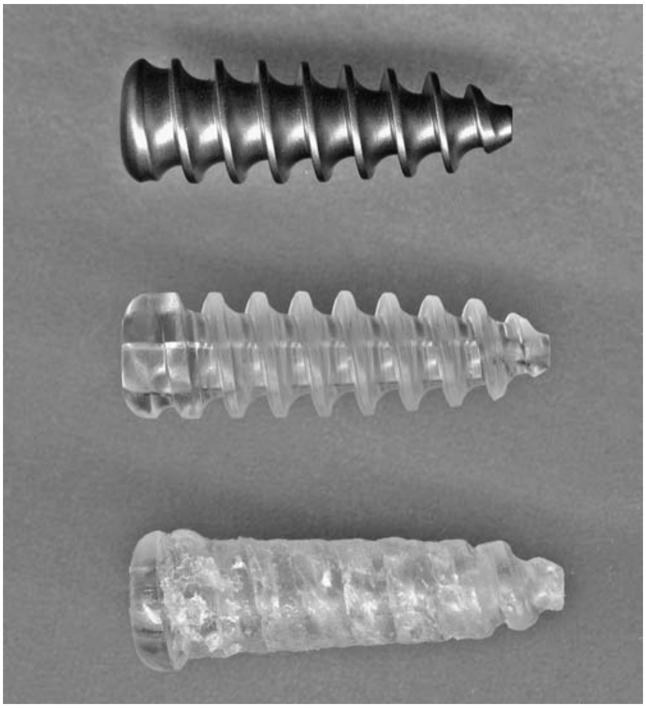

Figure 5. On retrieval, it was found that the bioabsorbable screws experienced thread compression during delivery/testing. This is evidenced by the intact titanium screw (top), an intact bioabsorbable screw (middle), and a retrieved absorbable screw (bottom).

the angle of graft loading increases. Individual statistical comparisons yielded statistically significant results ($P < .05$ for all comparisons) for each type of comparison of increasing angle. For both bioabsorbable and titanium screws, increasing the angle of pull significantly increased the failure loads. When we compared screw materials, the 60° position yielded significantly greater failure loads for the bioabsorbable screw compared with the titanium screw ($P < .0002$).

DISCUSSION

Authors of previous biomechanical studies of ACL graft fixation with interference screws examined construct stability by pulling in line with the bone tunnel.[1,2,9] Pavlik et al[27] described the effects of altering pull angle of bone–patellar tendon grafts in porcine femurs to evaluate the press-fit fixation technique. Significant differences in failure strength and stiffness between pulls at 0º, 15º, 30º, and 45º relative to the bone tunnel were reported. It was determined that higher failure loads and construct stiffness of the femoral press-fit constructs were exhibited when pull angles were increased.

No one has investigated changing pull angles when comparing bioabsorbable and metal interference screw fixation, a common method performed by orthopaedic surgeons. Previous studies have reported that using bioabsorbable interference screws yielded similar results as metal interference screws in ACL construct fixation.[13,18,32] However, no one has compared the stability of bioabsorbable and metal interference screw constructs while varying the angle of pull from the femoral tunnel. We investigated the effects of changing the angle of pull relative to the femoral tunnel using both PLLA and titanium interference screws for soft tissue ACL graft fixation.

Porcine knees have been previously used in the evaluation of ACL fixation devices.[1,18,26,29,33] In these studies, most of the graft slippage was found to occur within the first 100 cycles of loading between 10 and 150 N.[1,11,18,20] Kousa et al[18] reported mean failure loads and 200 cycle graft displacements of 589 N and 3 mm for bioabsorbable screws and 546 N and 2.9 mm for metal screws. However, these data were collected as separate tests, and thus the effects of cyclic loading on ultimate graft stability is unclear. Therefore, the difference in current results for 0º pull-out testing can be accounted for by the sequence of testing in the current study—that is, grafts were conditioned to lower failure loads by cyclic loading. This most likely caused our failure loads of 278 N and 260 N for PLLA and titanium, respectively, to be lower than the results of Kousa et al.[18] On the other hand, 200 cycle displacements of 2.9 mm for bioabsorbable and 3.3 mm for metal screws were comparable with the data (~3 mm) from Kousa et al.[18] However, the displacement values and loads to failure in our study are of concern because graft loads with activities of daily living are thought to be around 450 N.

Current results show a significant increase in failure load and decrease in graft displacement with respect to increased angles of pull for both screw types. The relatively low failure loads and large graft displacements indicate that pulling 0º with respect to the tunnel is the least stable position, because either graft material or interference screw can slide directly out of the insertion hole. At increased angles of pull, the entire length of the screw acts as a lever, maintaining contact forces that stabilize the graft. This counters the possibility that pulling at greater angles from the tunnel would create lower failure loads because of slippage between the graft and the interference screw or because of a shearing of the graft by the screw.

The results are concordant with those of previous authors who evaluated bioabsorbable and metal interference screws while pulling directly in line from the femoral tunnel, because there were no significant differences between the failure loads or graft displacements of the 2 screw types.[1,18,32] However, the results contrast with previous studies by indicating that bioabsorbable screws have significantly greater fixation strength relative to metal screws when grafts are loaded at angles greater than 0º from the femoral tunnel. At 30° pull, specimens with the bioabsorbable screw withstood a 50-N higher failure load and, at 60° pull, a 137-N higher failure load than the specimens with metallic screws. In a 2-way analysis of variance, the interaction term between screw type and angle of pull was significant. Thus, previous studies showing no statistical difference in construct stability for ACL grafts held with bioabsorbable and metal interference screws remain valid only when evaluating loads directly in line with the femoral tunnel, because differences appear and become increasingly marked at increased loading angles. This is relevant because in vivo, the ACL graft is subject to loads at 60º or more, relative to the femoral tunnel, as the leg approaches full extension. Furthermore, most postoperative rehabilitation programs are performed with the leg in a semi- to fully extended state, that is, standing and walking. The clinical implications of higher failure load and less graft elongation seen with the bioabsorbable screws could mean less concern initially with accelerated rehabilitation programs and a greater tolerance for rehabilitation performed in greater degrees of knee extension. In addition, because of the emphasis of early rehabilitation protocols on weightbearing with the knee in extension, femoral fixation devices that were previously evaluated by pulling in line with the femoral tunnel may necessitate analysis at increased angles of pull, because this may elicit different construct stabilities from prior results.

One possible explanation for our finding of better performance by the bioabsorbable screws is that the bioabsorbable screws provided a better press fit by applying a uniform compression of the tissue compared with the titanium screws. This phenomenon was confirmed after testing by retrieval of the bioabsorbable screws (Figure 5). The bioabsorbable screws were found to experience screw thread compression within the tunnel, and this likely increased the contact forces between the screw, graft, and bone. The bioabsorbable screws therefore would increase the stability of the construct at greater angles of pull because the tissue had less ability to slip past the screw. The metal screws, on the other hand, displace the tissue into the spaces adjacent to the threads of the screw and allow unwinding and slippage of the screw when loaded at an angle. In addition, because it was observed that the soft tissue grafts did not experience any tearing during failure testing, it can be concluded that the mechanism of failure was from graft slippage past the interference screw and not from the screw cutting into the graft. Therefore, the lower fixation strength of the metal screws cannot be attributed to the intact metal threads cutting through the graft.

Porcine specimens were used because of their controllable donor age and high consistency of bone quality relative to that of human cadaveric specimens.[1,18,25,29] Pena et al[28] recently emphasized the influence of bone mineral density on the in vitro ultimate failure loads in bone specimens from human donors. In human cadaveric specimens, it is often difficult to adequately account for varying bone mineral density differences across specimens for in vitro studies, and such issues could influence the results.[28,29] Nurmi et al[25] argued that porcine tibias were a poor substitute for human tibias because the surrogate underestimates graft slippage and overestimates failure load in ACL reconstructions. However, because in this study we evaluated the effects of changing angles of pull relative to the ACL femoral tunnel, it can be assumed that even though the values for graft displacement and failure load in porcine bone may not be the same as for normal human bone, the effects of changing pull angles on porcine bone should be similar to the effects of changing pull angles on human bone. Nevertheless, because mechanical properties of porcine specimens may not be similar to those of human specimens and because only specimens simulating an immediate postoperative condition were examined, we recognize that values obtained in this in vitro study cannot be completely extrapolated to ACL reconstruction procedures in human patients.[8,10,17,21,22] In addition, because this was an acute study of fixation strength using bioabsorbable screws, loss of screw-graft fixation because of material resorption could not be simulated but would be of potential clinical concern.

CONCLUSION

The results of this study indicate that when one is using either bioabsorbable PLLA or titanium interference screws for ACL graft fixation, the failure loads increase and the graft displacements decrease with angles of pull diverging from the femoral tunnel. In addition, although previous studies showed no significant difference in fixation strength between ACL repairs using bioabsorbable and metal interference screws when pulling directly in line with the femoral tunnel, this study shows that ACL grafts with bioabsorbable screws withstand significantly higher failure loads at increasing angles of pull relative to the femoral tunnel than do the same repairs with metal interference screws.

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