The 1:1 Versus the 2:2 Tunnel-Drilling Technique

Optimization of Fixation Strength and Stiffness in an All-Inside Double-Bundle Anterior Cruciate Ligament Reconstruction—a Biomechanical Study

Michael P. Walsh,* MD, Coen A. Wijdicks,* MSc, Bryan M. Armitage,* MD, MSc, Benjamin D. Westerhaus,* Josh B. Parker,[†] BS, and Robert F. LaPrade,*[‡] MD, PhD
*From the *Orthopaedic Biomechanics Laboratory, Department of Orthopaedic Surgery, University of Minnesota, Minneapolis, Minnesota, and the [†]Department of Veterinary Population Medicine, College of Veterinary Medicine, University of Minnesota, Saint Paul, Minnesota*

Background: Double-bundle anterior cruciate ligament (ACL) reconstructions involve drilling 2 tibial tunnels separated by a narrow 2-mm bone bridge. The sequence of reaming and drilling the tibial tunnels for double-bundle ACL reconstructions has not been defined.

Hypothesis: Fixing a graft in the posterolateral ACL tibial tunnel before reaming the anteromedial tibial tunnel will reduce the number of complications, as compared with drilling both the anteromedial and posterolateral tunnels before graft fixation, when performing double-bundle ACL reconstructions.

Study Design: Controlled laboratory study.

Methods: Twelve porcine tibias were divided into 2 groups of 6 specimens. Fresh bovine extensor tendons grafts were fixed in 7-mm tunnels reamed using an inside-out method. Grafts were fixed in a retrograde fashion with 7-mm bioabsorbable retrograde screws. The tibias in group 1 were reconstructed by reaming and reconstructing the posterolateral tunnel before reaming and securing the graft for the anteromedial tunnel (ie, 1:1 method), whereas those in the second group were reconstructed by reaming both tunnels before graft fixation in either (ie, the 2:2 method). The specimens were biomechanically tested with cyclic and load-to-failure parameters.

Results: Cyclic testing revealed no significant difference between the 2 methods in displacement or stiffness. In load-to-failure testing, the 1:1 group withstood significantly higher initial failure loads and ultimate loads. Pullout displacement was significantly higher for the 1:1 group. Whereas no tibias in the 1:1 group sustained fractures, 4 from the 2:2 group demonstrated a bone bridge fracture.

Conclusion: Soft tissue ACL grafts fixed in the tibia with the 1:1 method withstood significantly higher initial and ultimate failure loads and were stiffer than the grafts fixed with the 2:2 method. Tibias fixed with the 1:1 method were also less susceptible to bone bridge fracture.

Clinical Relevance: The potential for a lower complication rate and greater pullout strength seen with the 1:1 method may prove useful to surgeons performing anatomic double-bundle ACL reconstructions, in addition to other procedures involving reconstructing 2 closely positioned tunnels, including anatomic posterolateral corner and medial collateral reconstructions.

Keywords: all-inside anterior cruciate ligament reconstructions; double-bundle anterior cruciate ligament; soft tissue anterior cruciate ligament graft fixation; 1:1 method; 2:2 method; anterior cruciate ligament

[‡]Address correspondence to Robert F. LaPrade, MD, PhD, Professor, Sports Medicine and Shoulder Surgery, Director, University of Minnesota Orthopaedic Biomechanics Laboratory, Department of Orthopaedic Surgery, University of Minnesota, 2450 Riverside Avenue South, R200, Minneapolis, MN 55454 (e-mail lapra001@umn.edu).

No potential conflict of interest declared.

The American Journal of Sports Medicine, Vol. 37, No. 8
DOI: 10.1177/0363546509333013

The anterior cruciate ligament (ACL) is composed of 2 functional bundles—namely, the anteromedial bundle and the posterolateral bundle, as defined by their tibial attachments.[34,39,46,47,50,58-60] To date, most ACL reconstructions are performed as single-bundle reconstructions, from 50 000 to 100 000 per year,[19,26] thereby making ACL reconstructions the sixth most common orthopaedic procedure performed in the United States.[3] However, some have reported that there is a subset of patients (range, 10% to 40%) who remain subjectively unstable and/or unable to regain preinjury functionality.[5,16] In addition, degenerative joint disease may be associated with traditional single-bundle ACL reconstructions in as many as 90% of cases at 7-year follow-up.[14] Because of statistics such as these, interest in anatomical double-bundle ACL reconstructions has increased.

Some studies have compared single-bundle ACL reconstructions to double-bundle ACL reconstructions for anterior tibial translation,[41] internal rotation,[18,42,55] and pivot shift.[11,18,29,35,45,51,57] Furthermore, double-bundle reconstructions involve drilling 2 tunnels, separated by a bone bridge as narrow as 2 mm; such reconstructions are accompanied by risks of avascular necrosis, bone bridge and tibial plateau fracture, graft impingement, and increased difficulty in revision cases.[61] Poor tunnel placement (when done via currently established methods) may also lead to a merging of the anteromedial and posterolateral tunnels, thereby making double-bundle ACL reconstruction very difficult. Moreover, there are concerns that drilling 4 tunnels for these reconstructions may lead to problems with bone stock due to tunnel enlargement.[1,11,44] One study reported evidence of communication between the 2 tibial tunnels on MRI at 1 year postoperatively in 41% of patients.[44]

Because drilling 2 tunnels in close proximity creates an environment susceptible to fracture, optimization of this vulnerable technique could be important for double-bundle ACL reconstruction outcomes. However, no comparisons of single- versus double-bundle ACL reconstructions have been published in regard to fixation strength or stiffness following reconstruction.

The purpose of this study was to examine 2 tibial tunnel-drilling techniques using all-inside reconstruction. Our hypothesis was as follows: Securing a graft and screw in the posterolateral ACL tibial tunnel before reaming the anteromedial tibial tunnel will reduce the number of complications (eg, bone bridge fracture) seen as a result of drilling the anteromedial and posterolateral tunnels before graft fixation in either tunnel during double-bundle ACL reconstruction. An additional purpose of the study was to determine whether there was a difference in fixation strength and stiffness resulting from (1) securing the posterolateral ACL bundle before drilling the anteromedial tunnel (ie, the 1:1 method) or (2) drilling both tunnels before ligament insertion and fixation (ie, the 2:2 method).

MATERIALS AND METHODS

Twelve proximal, skeletally mature, fresh-frozen, intact porcine tibias (obtained from the Department of Animal Science, University of Minnesota, St Paul) and 24 fresh bovine extensor tendons (Frontier BioMedical, Logan, Utah) were used to determine cyclic displacement (mm), cyclic stiffness (N/mm), initial failure load (N), ultimate load (N), pullout displacement (mm), and pullout stiffness (N/mm) for varying fixation techniques for all-inside double- and single-bundle ACL tibial tunnel reconstructions. The tibias had no signs of previous injury, abnormality, or disease; in addition, the tendons were free from any damage along their length. The tendons were stored in 0.9% saline solution at –20°C before graft preparation. The tibias were also stored in a freezer at –20°C before ACL reconstruction.

Bone Mineral Density Analysis

An analysis of the bone mineral density of the specimens was performed before biomechanical testing. Each sample was scanned in duplicate by dual energy x-ray absorptiometry using a GE Lunar Prodigy Advance scanner (General Electric, Milwaukee, Wisconsin) for determination of bone mineral density (g/cm^2). The region of interest included the proximal tibia, to 14 cm distal to the tibial plateau and its surrounding soft tissues. Eighteen specimens were scanned, and 12 of those were found to have bone mineral density values that met the inclusion criteria of values comparable to those of a young athletic population (range, 1.24-1.62 g/cm^2) (see Table 1).[2,37,38,40]

Specimen Preparation

Specimens were thawed in a 2°C refrigerator before dissection and consequent biomechanical testing. The tibial diaphysis was cut 14 cm distal to the tibial plateau with an oscillating bone saw. The distal end of the tibia was then placed inside a 6- × 5-cm metal cylinder and filled with polymethylmethacrylate (Dentsply, York, Pennsylvania). Two screws were fixed into opposing sides of the distal tibia, with approximately 1 cm of the screw remaining outside the cortex, to ensure static fixation of the tibia in the polymethylmethacrylate before potting.

All grafts obtained from the supplier (Frontier BioMedical) were sharply trimmed to be of equal size. After preparation, total graft length was 150 mm (Figure 1), and their diameters were 7 mm when the grafts were doubled over. The tendons were wrapped in saline-soaked gauze and kept at room temperature for 30 minutes before preparation. The ends of the allograft were marked with a surgical marker at 25 mm from each end and then separately whipstitched[8] with a modified technique using a No. 2 continuous braided polyester/polyethylene suture loop (FiberLoop; Arthrex Inc, Naples, Florida) from the 25-mm mark to the end of the ACL graft (Figure 1). The diameters of the doubled-over prepared grafts were measured to be 7 mm by pulling them through a graft sizing block.

Surgical Technique—All Inside Method

One surgeon (R.F.L.) drilled all the ACL tunnels, to reduce variance in surgical skill. All grafts were fixed with a combination of a 7-mm diameter retrograde bioabsorbable

TABLE 1
Specimen and Biomechanical Testing Results for the 2 Drilling Techniques

Group: Specimen	Bone Mineral Density, g/cm^2	Cyclic Displacement, mm	Cyclic Stiffness, N/mm	Failure Load Initial, N	Failure Load Ultimate, N	Pullout Displacement, mm	Pullout Stiffness, N/mm
2:2							
1	1.70	0.8	243	1035	1085	4.6	250
2	1.51	1.2	169	443	523	2.7	193
3	1.74	0.8	247	794	838	3.9	219
4	1.16	3.2	63	353	383	1.9	192
5	1.18	1.4	147	802	939	7.1	130
6	1.22	1.5	137	528	574	3.3	172
Mean ± SD	1.42 ± 0.27	1.5 ± 0.9	168 ± 70	659 ± 260	723 ± 272	3.9 ± 1.8	193 ± 41
1:1							
1	1.63	1.2	172	1011	1193	8.7	135
2	1.48	1.1	189	1355	1396	7.2	190
3	1.49	0.8	238	1206	1342	8.8	155
4	1.20	1.9	106	902	989	9.6	98
5	1.15	1.2	169	876	938	6.2	147
6	1.49	1.0	204	1493	1588	7.7	211
Mean ± SD	1.41 ± 0.19	1.2 ± 0.4	180 ± 44	1140 ± 252	1241 ± 250	8.0 ± 1.2	156 ± 40
P	.69	.70	.72	.0087	.0064	.0014	.1476

Figure 1. Extensor tendon graft was prepared to be 150 mm in length, with each end whipstitched 25 mm into the graft (graduated interdigitations, 5 mm).

interference screw and a 2-holed titanium suture button (Figure 2). Tibias were divided into 2 test groups (n = 6 per group) with the resultant mean bone mineral density being equal between each group (see Table). The first group consisted of the double-bundle reconstruction using the 1:1 method of tunnel formation (1:1 group), and the second group, the 2:2 method (2:2 group).

1:1 tunnel and fixation method. In the 1:1 group, we employed a method of tunnel formation and graft fixation that involved, in succession, drilling the posterolateral tunnel and fixing the posterolateral bundle ACL graft in its tibial tunnel and then drilling the anteromedial tunnel and fixing the anteromedial bundle graft in its tunnel. This method of tunnel reaming and graft fixation was defined as the 1:1 method (Figure 3).

2:2 tunnel and fixation method. For the 2:2 group, we used a method for tibial tunnel formation and graft fixation that involved reaming the 2 tunnels successively, 1 directly after the other, and then fixing the grafts in their respective tibial tunnels in a consecutive manner, following the formation of the 2 tunnels. This method of tunnel reaming and graft fixation was defined as the 2:2 method (Figure 3).

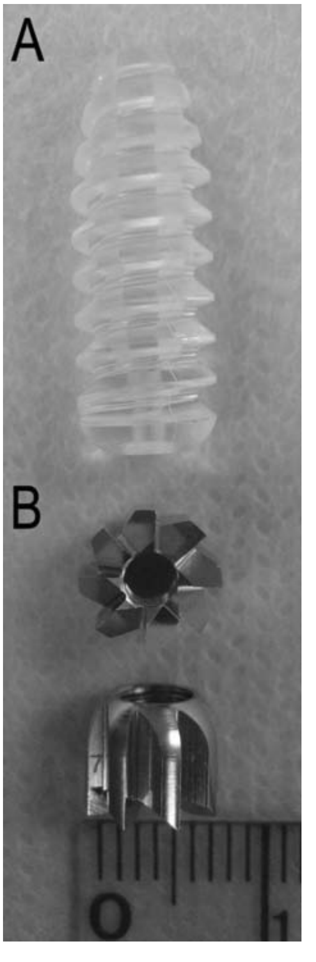

Figure 2. A, 7-mm retrograde bioabsorbable screw. B, 7-mm retrograde drill bit.

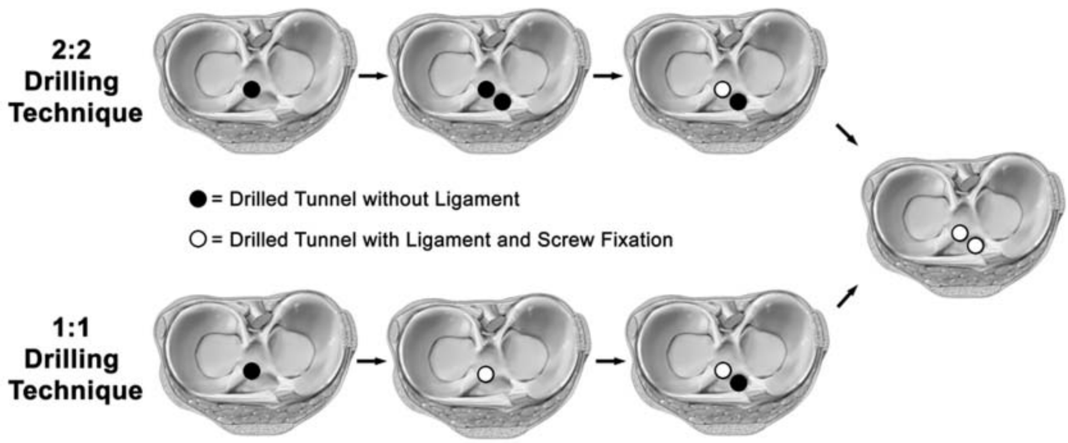

Figure 3. Illustration comparing the tunnel drilling technique of the 1:1 and 2:2 methods.

Tunnel formation. Both fixation methods used identical tibial tunnel-reaming techniques. A tibial ACL adapter drill guide (Arthrex Inc, Naples, Florida) was placed over the previously established porcine tibial ACL footprint,[17,30] starting with the posterolateral border of the ACL footprint in the most posterior aspect of the region between the tibial eminences,[27] to ream the posterolateral tunnel. For the anteromedial tunnel, the adapter drill guide was placed in the anteromedial border of the ACL footprint; a bone bridge of 2 mm remained between the 2 tunnels at the joint line, whereas a distance of 2 cm separated the tunnels distally on the tibial metaphysis, thereby creating 2 diverging tunnels. For the 1:1 group, the anteromedial tunnel was drilled only after the posterolateral bundle graft was secured in its tunnel, whereas for the 2:2 group, the anteromedial tunnel was drilled immediately after the posterolateral tunnel. To ream the posterolateral tunnel, the surgeon positioned the drill sleeve on the tibial cortex approximately 3.5 cm medial to the tibial tuberosity, at an angle of 45° to the sagittal plane of the long axis of the tibia, based on position measurements previously described in the literature.[44,48] For the anteromedial tunnel, the drill sleeve was positioned on the tibial cortex approximately 1.5 cm medial to the tibial tuberosity, at an angle of 45° to the sagittal plane of the long axis of the tibia. The guide pin was advanced superiorly and then engaged with a 7-mm retrograde drill bit. The drill bit disengaged from its original position on the adapter as it engaged with the guide pin. On the guide pin, a black rubber O-ring was pushed to the end of the drill sleeve superiorly, to determine the starting point of the tibial socket. Retrograde force on the drill was applied, and the O-ring traveled 25 mm from the original position on the drill guide, thus creating a 25-mm all-inside tibial socket. After removal of the retrograde reamer, the tunnel depth was verified with a depth gauge. A No. 2 nonabsorbable polyester/polyethylene suture (FiberStick, Arthrex) was then passed through the cannulation of the retrograde drill guide pin, and the end of the suture was tied into a loop. The whipstitched graft sutures were then placed through the suture loop and pulled distally through the tibial tunnel via the suture loop. Both ends of the graft were then pulled inside the 25-mm tibial tunnel, and the 4 strands of whipstitch suture were pulled distally outside the tibial cortex.

Graft fixation. In the 1:1 group and the 2:2 group, grafts were secured in the tibial tunnels in an identical manner. A cannulated hex-tipped retrograde screwdriver was passed proximally (antegrade) through the tibial tunnels, and a 7- × 20-mm poly-L-lactide bioabsorbable retrograde screw (RetroScrew, Arthrex) (Figure 2) was secured to the screwdriver. Screws were fixed such that they were positioned on the tunnel wall opposite of the probable bone bridge wall (1:1 method) or the already established bone bridge wall (2:2 method), thereby resulting in a construct where the grafts—rather than the screws—were in direct contact with the bone bridge. The retrograde screw was screwed counterclockwise to engage it into the tibial tunnel, flush with the tibial plateau. Next, a 9.0- × 3.5-mm 2-holed titanium suture button (Arthrex) was used to secure the 4 whipstitch suture tails by tying the sutures via a previously described method.[53]

Biomechanical testing. The tibial specimens were mounted into an Instron 5865 tester (Instron Systems, Norwood, Massachusetts) in a customized apparatus that enabled the displacement force vector to be applied in direct alignment with a vector made by the 2 tibial tunnels. Mounting of the looped free ends of the grafts was achieved by inserting 3.5-mm aluminum rods through the loops and fixing the potted tibias into a customized apparatus to replicate the pull of the femoral ACL attachment sites (Figure 4). The method of pulling on the graft loops with aluminum rods was based on prior reports of suboptimal results with ACL soft tissue graft clamping due to a rise of stress on the graft and slippage.[54] The distance from the entrance of the bone tunnel to the rod was 50 mm, to simulate the reported intra-articular space of the ACL (30 mm) and femoral tunnel length (20 mm).[31]

Loading data were recorded by Bluehill software (Instron Systems) at a rate of at least 100 Hz. The grafts were isolated and preconditioned from 10 to 50 N at 0.1 Hz for 10 cycles, which allowed for a starting point between all tested specimens and the ability to compare between different

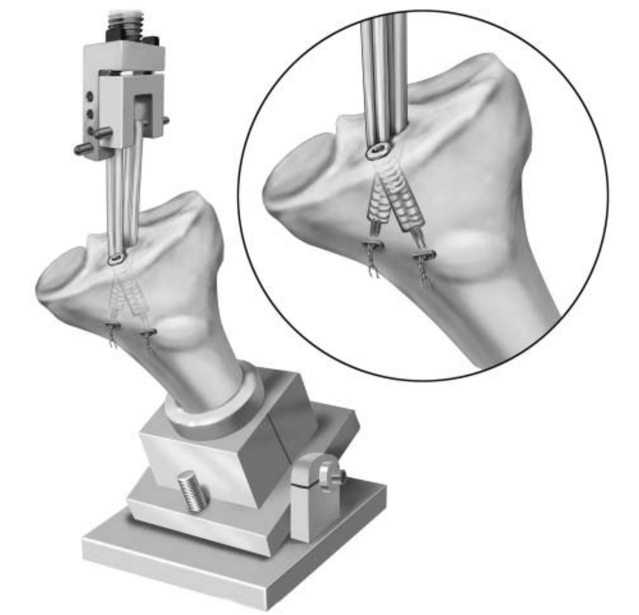

Figure 4. Illustration of the left tibia demonstrating the double-bundle retrograde bioabsorbable screw and suture button group mounted on a customized apparatus to enable the displacement force vector to be applied in direct alignment with the tibial tunnel. Proximal ends of the grafts were secured with aluminum dowels through the looped ends. Tibias were potted in polymethylmethacrylate to allow for a solid fixation in the apparatus.

fixation techniques. The grafts were then immediately subjected to cyclic loading, under repeated loads, for 500 cycles between 50 and 250 N at a frequency of 1 Hz: the loads simulate previously measured forces in the ACL during passive extension at the knee[32]; the frequency of 1 Hz simulates the reported frequency of walking[24]; and the number of cycles (n = 500) was chosen to simulate an early rehabilitation protocol of flexion-extension loading on the reconstructed graft.[54] Immediately after cyclic testing was completed, the grafts were further displaced at 20 mm per minute until failure, and the mechanism of failure was subsequently noted. Cyclic displacement (mm), cyclic stiffness (N/mm), initial failure load (N), ultimate load (N), pullout displacement (mm), and pullout stiffness (N/mm) were determined. The ultimate load was defined as the maximum endured load during testing. In addition, ultimate elongation was defined as the displaced length of the ligament at the ultimate load. Stiffness was calculated as the slope of the linear region of the load-elongation curve corresponding to the steepest straight-line tangent to the curve. Because prior reports indicated decreased tissue stiffness and strength with desiccation,[22] tissues were frequently hydrated with a saline-filled spray bottle during all stages of specimen preparation and testing of the tissues. Measurements were analyzed and plotted with Microsoft Excel (Microsoft Corp, Redmond, Washington).

Statistical analysis. Statistical analysis was performed with SAS (SAS Institute, Cary, North Carolina). We compared the bone mineral density, initial failure load, ultimate

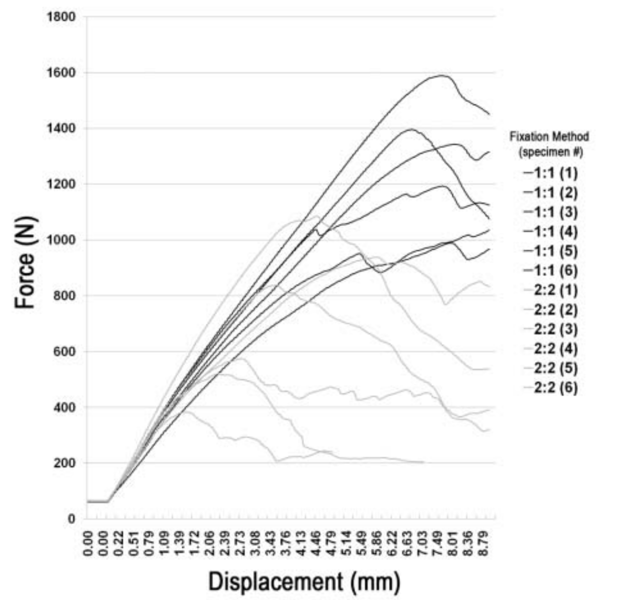

Figure 5. Load-displacement curves for all the examined specimens to determine initial failure load (N), ultimate load (N), pullout displacement (mm), and pullout stiffness (N/mm). Grafts displaced at 20 mm per minute until failure.

failure load, pullout displacement, and pullout stiffness for each fixation group using a 2-way analysis of variance. Cyclic displacement and cyclic stiffness were not normally distributed and were thus analyzed with a Friedman 2-way analysis of variance of ranks, a nonparametric procedure. Post hoc Tukey tests were conducted to assess whether there was a significant difference between fixation techniques (1:1 group versus 2:2 group) for failure testing results. Significance was set at $P < .05$.

RESULTS

Table 1 presents the biomechanical test results. Twelve specimens that were scanned via dual energy x-ray absorptiometry (mean, 1.41 ± 0.22 g/cm^2; range, 1.15-1.74) met the bone mineral density inclusion criteria. There were no significant differences in bone mineral densities between the 2 groups.

During cyclic testing, there was no significant difference in cyclic displacement between the 1:1 group (1.2 ± 0.4 mm) and the 2:2 group (1.5 ± 0.9 mm). Furthermore, there was no significant difference in the cyclic stiffness between the 1:1 group (180 ± 44 N/mm) and the 2:2 group (168 ± 70 N/mm).

In load to failure testing, there was a significantly higher initial failure load for the 1:1 group (1140 ± 252 N) compared with the 2:2 group (659 ± 260 N; $P < .01$). The ultimate failure loading demonstrated a similar significantly higher load in the 1:1 group (1241 ± 250 N) compared with the 2:2 group (723 ± 272 N; $P < .01$) (Figure 5). Pullout displacement was significantly higher for the 1:1 group (8.0 ± 1.2 mm) than the 2:2 group (3.9 ± 1.8 mm; $P < .01$). There was no significant difference between pullout stiffness for the 1:1 group (156 ± 40 N/mm) and the 2:2 group (193 ± 41 N/mm).

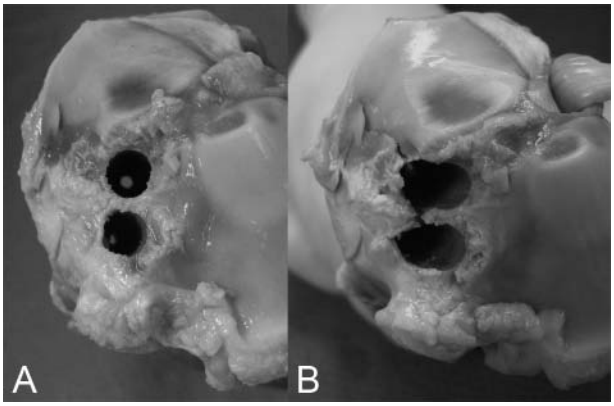

Figure 6. Representative right tibia specimen from the 2:2 fixation group before biomechanical testing (A) and after (B).

Modes of failure were consistent between groups; specimens failed by complete pullout of a limb of the graft from the screw-tendon interface. After the screws were removed posttesting, no notable fractures were seen in the tibias drilled and fixed with the 1:1 method. However, 4 of 6 tibias from the 2:2 group (specimens 2, 3, 4, 6) demonstrated a fracture through the bone bridge, in some cases extending along the tibial plateau (Figure 6).

DISCUSSION

This study tested tibias that underwent double-bundle ACL reconstruction via the 1:1 method—that is, by drilling and securing the posterolateral ACL bundle in its tunnel before drilling and securing the anteromedial ACL bundle in its tunnel. As such, these tibias were able to withstand significantly higher initial and ultimate failure loads (Figure 5) when compared to the tibias reconstructed via the 2:2 method—that is, by drilling both anteromedial and posterolateral tunnels before graft fixation. Fixation in the 1:1 group also showed significantly higher pullout displacement than did the 2:2 group, and there was no significant difference between pullout stiffness for the 1:1 group versus the 2:2 group. We also discovered that tibias fixed with the 1:1 method had fewer bone bridge fractures than did those fixed with the 2:2 method.

Throughout this study, we noted that in the tibias drilled and fixed using the 1:1 method, there were no fractures of the bone bridge; among the tibias drilled and fixed with the 2:2 method, 4 sustained fractures of the bone bridge with communication between the tunnels. This increase in fractures may be a result of stress placed on the 2-mm bone bridge and adjacent anteromedial tunnel during graft and screw insertion and subsequent fixation in the posterolateral tunnel.

A problem that is unique to double-bundle ACL reconstruction is fracture through the narrow bone bridge separating the anteromedial and posterolateral tunnels. An all-inside technique may reduce the amount of tunnel widening seen with transtibial ACL reconstructions[13,20,44]; however, graft fixation at or near the joint line in double-bundle reconstruction may actually carry an increased risk of fracture, especially through the narrow bone bridge.[61] Because the retrograde screws used in this system were fixed at the joint line, they put increased stress at the location where the bone bridge was at its narrowest; that is, the tunnels diverge while coursing distally in the tibia. Although these hypotheses have not been biomechanically proven or disproven, studies have reported that the insertion of a bioabsorbable interference screw itself increases the diameter of the bone tunnel through disturbance of cancellous bone.[6] Moreover, any sudden change in geometry or density—such as fastening a screw only 2 mm away from a vacant tunnel—may cause a localization of stress.[9,10,15,21,23] As such, with only 2 mm separating the ACL double-bundle tibial tunnels, protrusion of a screw into the neighboring cancellous bone quite possibly leads to disturbance of the other, vacant tunnel and so may contribute to a possible fracture between the tunnels. This notion was supported by a study that showed communication between tunnels to be a common occurrence, 1 year postoperatively (41%).[44]

Through a literature review and the current experiment, we have arrived at the following explanation for our findings: The insertion of a ligament into a drilled hole with an interference screw creates hoop stresses arising from the pressure of the ligament against the walls of the tunnel. These hoop stresses produce a stress field that is dependent on the surrounding anatomy of the bone. When using the described 2:2 drilling technique, the energy imparted into the bone through this stress field distributes around the second tunnel. Therefore, when the second ligament was secured with its interference screw, the stress field created by the second ligament fixation in its tunnel was additive to the first. We theorize that this resulted in very high stresses between the 2 insertion points that could result in earlier catastrophic failure of the construct. However, if the second tunnel was not already reamed when the first ligament was placed, the hoop stresses would distribute through the bone matrix where the second hole would be placed. The second tunnel was then drilled through a prestressed matrix, thereby resulting in a reduction in stored energy through strain relief of the bone localized to the tunnel. The 1:1 drilling technique could decrease the additive affects of the second graft fixation and so cause less disruption to the mechanical stability of the bone matrix, thereby increasing the integrity of the bone/implant construct.

This occurrence has been implicated in previous experiments regarding the result of screw holes on bone strength,[25,33] the authors of which indicated a decrease in strength as being caused by a decrease in substance available to resist load, in addition to a concentration of stress caused by a break in the cortex. Furthermore, individual vacant screw holes experience a threefold increase in stress concentrations as compared to that of intact bone,[4] which may lead to deformation of the vacant tunnel during interference screw fixation, thus leading to increased susceptibility to fracture at or around the vacant tibial tunnel. This may also contribute to tunnel distortion, plateau fracture, or bone bridge fracture and subsequently lead to tunnel widening and failure of graft fixation, as seen in the present study. A structure resists loads best when it is shaped like a cylinder[4,9,10,15,21,49,52] and fractures occur because of an inertial weakness or a local weakness in the bone[15]; as such, by deforming the vacant anteromedial tibial tunnel during graft fixation in the posterolateral tibial tunnel, we may have been creating a fracture during fixation or a nidus that produced the fracture during biomechanical testing when reconstructing tibias using the 2:2 method. Thus, we believe that a technique may remedy this situation—namely, one in which the surgeon drills the posterolateral tunnel and fills it with the graft and screw before drilling the anteromedial tunnel.

Although an extensive literature review did not produce a study design comparable to the present one, our laboratory has published pullout values for single-bundle ACL reconstructions using the same fixation devices and testing protocols used here.[53] Tibias were reconstructed with a single 9-mm all-inside tunnel, a 9-mm diameter bovine extensor graft, a 9-mm retrograde bioabsorbable screw, and titanium suture buttons as backup and then subjected to cyclic and load-to-failure testing. The reported results are listed as follows and can be compared to the results from the present study, which used two 7-mm tunnels, two 7-mm grafts, and two 7-mm retrograde bioabsorbable screws, in addition to titanium suture buttons.

Whereas the current study showed cyclic displacements of 1.2 ± 0.4 mm and 1.5 ± 0.9 mm in the 1:1 and 2:2 groups, respectively, cyclic displacement in the prior study was 1.40 ± 0.34 mm. In addition, the cyclic stiffness values in the current study were 180 ± 44 N/mm for the 1:1 group and 168 ± 70 N/mm for the 2:2 group, whereas it was 161.93 ± 61.81 N/mm in the single-bundle study. Furthermore, initial failure loads in the current study were reported as 1140 ± 252 N and 659 ± 260 N for the 1:1 and 2:2 groups, respectively; in the prior study, the initial failure load was 873.87 ± 148.74 N. Regarding ultimate failure loads, the values in the present study were 1241 ± 250 N for the 1:1 group and 723 ± 272 N for the 2:2 group, as compared with that in the single-bundle reconstruction study, which was 1027 ± 157 N. In the present study, pullout stiffness values were 156 ± 40 N/mm and 193 ± 41 N/mm for the 1:1 and 2:2 groups, respectively; in the prior study, the pullout stiffness was 152.50 ± 46.37 N/mm. Furthermore, although no tibias in the 1:1 group sustained fractures, 4 of 6 tibias from the 2:2 group demonstrated a fracture through the bone bridge, which can be compared with the prior single-bundle study, in which no tibial fractures were discovered and there were no instances of retrograde screw migration out of the tibial tunnel nor any cases of either the suture button knot failing or the suture button itself failing.

A limitation of the current study was that we used porcine tibias and bovine extensor tendons rather than human specimens. It would be ideal to obtain specimens from human cadavers for testing—that is, if we could obtain a sufficient number of cadaveric samples from young active humans. However, cost, sufficient numbers, and the fact that most available specimens are from elderly cadavers (and so do not have the same material qualities as young human specimens) make it difficult to use human specimens.[36] Moreover, the porcine tibia model has been described as an effective means for biomechanical testing[7,28,43,56]; furthermore, bovine extensor tendons are reportedly suitable replacements for human soft tissue grafts because they have structural properties similar to those of a double-looped semitendinosus and gracilis graft from young humans.[12] Therefore, we believed that it was acceptable to use these tissues in place of human tissues.

Another limitation was that we tested only tibial-side fixation methods. Although the tibia is regarded as the weaker point of ACL graft fixation,[28,30,51] information on the fixation strength and durability of femoral-side double-bundle ACL tunnels would be beneficial and thus should be researched in future studies. Because the femur is the stronger point of fixation, the 1:1 method may not be as critical to femoral fixation as it is to tibial fixation; in addition, many surgeons use cancellous or cortical-cancellous suspension aparati on the femoral side without a backup interference screw. Information pertaining to surgical technique in an intact human knee should be the topic of future research. One recently published study reported using a version of the 1:1 technique on the tibial side but only after drilling both femoral tunnels[49]; by doing so, this method may reduce the risk of damaging the posterolateral bundle graft while drilling.

In summary, tibias undergoing double-bundle ACL reconstructions using the 1:1 method were able to withstand significantly higher initial and ultimate failure loads than were tibias fixed using the 2:2 method. The tibias in the 1:1 group also showed a lower complication rate than those in the 2:2 group; complications included 4 bone bridge fractures and 1 tibial plateau fracture in the 2:2 group. Evidence of a lower complication rate and greater pullout strength when comparing the 1:1 and the 2:2 double-bundle ACL graft fixation method may prove useful to surgeons performing anatomic double-bundle ACL reconstructions, in addition to other procedures that involve drilling and reconstructing 2 closely positioned tunnels, including anatomic double-bundle posterior cruciate, posterolateral corner, and medial collateral reconstructions.

ACKNOWLEDGMENT

The authors acknowledge Conrad Lindquist for his work on preparing the testing fixture. We also mention Paul Lender for his statistical expertise. This project was supported by the Sports Medicine Research Fund of the Minnesota Medical Foundation.

REFERENCES

1. Ahn JH, Lee SH. Anterior cruciate ligament double-bundle reconstruction with hamstring tendon autografts. *Arthroscopy.* 2007;23:109, e1-e4.
2. Alfredson H, Nordstrom P, Lorentzon R. Total and regional bone mass in female soccer players. *Calcif Tissue Int.* 1996;59:438-442.
3. American Board of Orthopaedic Surgery. Research committee report. *Diplomatic Newsletter.* 2004:8.

4. Bechtol CO. Engineering principles applied to orthopedic surgery. *Instr Course Lect.* 1952;9:257-264.
5. Biau DJ, Tournoux C, Katsahian S, Schranz P, Nizard R. ACL reconstruction: a meta-analysis of functional scores. *Clin Orthop Relat Res.* 2007;458:180-187.
6. Buelow JU, Siebold R, Ellermann A. A prospective evaluation of tunnel enlargement in anterior cruciate ligament reconstruction with hamstrings: extracortical versus anatomical fixation. *Knee Surg Sports Traumatol Arthrosc.* 2002;10:80-85.
7. Chang HC, Nyland J, Nawab A, Burden R, Caborn DN. Biomechanical comparison of the bioabsorbable RetroScrew system, BioScrew XtraLok with stress equalization tensioner, and 35-mm Delta Screws for tibialis anterior graft-tibial tunnel fixation in porcine tibiae. *Am J Sports Med.* 2005;33:1057-1064.
8. Charlick DA, Caborn DN. Technical note: alternative soft-tissue graft preparation technique for cruciate ligament reconstruction. *Arthroscopy.* 2000;16:e20.
9. Cochran GVB. Biomechanics of orthopedic materials. In: *A Primer of Orthopedic Biomechanics.* New York, NY: Churchill Livingstone; 1982:143-216.
10. Cochran GVB. Biomechanics of orthopedic materials. In: *A Primer of Orthopedic Biomechanics.* New York, NY: Churchill Livingstone; 1982:71-142.
11. Colombet P, Robinson J, Jambou S, Allard M, Bousquet V, de Lavigne C. Two-bundle, four-tunnel anterior cruciate ligament reconstruction. *Knee Surg Sports Traumatol Arthrosc.* 2006;14:629-636.
12. Donahue TL, Gregersen C, Hull ML, Howell SM. Comparison of viscoelastic, structural, and material properties of double-looped anterior cruciate ligament grafts made from bovine digital extensor and human hamstring tendons. *J Biomech Eng.* 2001;123:162-169.
13. Fauno P, Kaalund S. Tunnel widening after hamstring anterior cruciate ligament reconstruction is influenced by the type of graft fixation used: a prospective randomized study. *Arthroscopy.* 2005;21:1337-1341.
14. Fithian DC, Paxton EW, Stone ML, et al. Prospective trial of a treatment algorithm for the management of the anterior cruciate ligament-injured knee. *Am J Sports Med.* 2005;33:335-346.
15. Frankel VH, Burstein AH. The biomechanics of refracture of bone. *Clin Orthop Relat Res.* 1968;60:221-225.
16. Freedman KB, D'Amato MJ, Nedeff DD, Kaz A, Bach BR Jr. Arthroscopic anterior cruciate ligament reconstruction: a metaanalysis comparing patellar tendon and hamstring tendon autografts. *Am J Sports Med.* 2003;31:2-11.
17. Fuss FK. Anatomy and function of the cruciate ligaments of the domestic pig (*Sus scrofa domestica*): a comparison with human cruciates. *J Anat.* 1991;178:11-20.
18. Gabriel MT, Wong EK, Woo SL, Yagi M, Debski RE. Distribution of in situ forces in the anterior cruciate ligament in response to rotatory loads. *J Orthop Res.* 2004;22(1):85-89.
19. Giffin JR, Vogrin TM, Zantop T, Woo SL, Harner CD. Effects of increasing tibial slope on the biomechanics of the knee. *Am J Sports Med.* 2004;32:376-382.
20. Giron F, Aglietti P, Cuomo P, Mondenelli N, Ciardullo A. Anterior cruciate ligament reconstruction with double-looped semitendinosus and gracilis tendon graft directly fixed to cortical bone: 5-year results. *Knee Surg Sports Traumatol Arthrosc.* 2005;13:81-91.
21. Gozna ER. Biomechanics of long bone injuries. In: Gozna ER, Harrington IJ, Evans DC, eds, *Biomechanics of Musculoskeletal Injury.* Baltimore, MD: Williams & Wilkins; 1982:1-22.
22. Haut RC, Powlison AC. The effects of test environment and cyclic stretching on the failure properties of human patellar tendons. *J Orthop Res.* 1990;8(4):532-540.
23. Haynes WC. Biomechanics of fracture treatment. In: Heppenstall RB, ed, *Fracture Treatment and Healing.* Philadelphia, PA: WB Saunders Co, 1980:124-163.
24. Honl M, Carrero V, Hille E, Schneider E, Morlock MM. Bone-patellar tendon-bone grafts for anterior cruciate ligament reconstruction: an in vitro comparison of mechanical behavior under failure tensile loading and cyclic submaximal tensile loading. *Am J Sports Med.* 2002;30:549-557.
25. Johnson BA, Fallat LM. The effect of screw holes on bone strength. *J Foot Ankle Surg.* 1997;36:446-451.
26. Johnson DL, Fu FH. Anterior cruciate ligament reconstruction: why do failures occur? *Instr Course Lect.* 1995;44:391-406.
27. Kondo E, Yasuda K, Ichiyama H, Azuma C, Tohyama H. Radiologic evaluation of femoral and tibial tunnels created with the transtibial tunnel technique for anatomic double-bundle anterior cruciate ligament reconstruction. *Arthroscopy.* 2007;23:869-876.
28. Kousa P, Jarvinen TL, Vihavainen M, Kannus P, Jarvinen M. The fixation strength of six hamstring tendon graft fixation devices in anterior cruciate ligament reconstruction, part II: tibial site. *Am J Sports Med.* 2003;31:182-188.
29. Lie DT, Bull AM, Amis AA. Persistence of the mini pivot shift after anatomically placed anterior cruciate ligament reconstruction. *Clin Orthop Relat Res.* 2007;457:203-209.
30. Lubowitz JH. No-tunnel anterior cruciate ligament reconstruction: the transtibial all-inside technique. *Arthroscopy.* 2006;22:900, e1-e11.
31. Magen HE, Howell SM, Hull ML. Structural properties of six tibial fixation methods for anterior cruciate ligament soft tissue grafts. *Am J Sports Med.* 1999;27:35-43.
32. Markolf KL, Gorek JF, Kabo JM, Shapiro MS. Direct measurement of resultant forces in the anterior cruciate ligament: an in vitro study performed with a new experimental technique. *J Bone Joint Surg Am.* 1990;72:557-567.
33. Muller ME, Allgower M, Schneider R, et al. *Manual of Internal Fixation.* New York, NY: Springer-Verlag; 1979:148-149.
34. Müller W. *The Knee: Form, Function, and Ligament Reconstruction.* New York, NY: Springer-Verlag; 1983:314.
35. Muneta T, Sekiya I, Yagishita K, Ogiushi T, Yamamoto H, Shinomiya K. Two-bundle reconstruction of the anterior cruciate ligament using semitendinosus tendon with endobuttons: operative technique and preliminary results. *Arthroscopy.* 1999;15:618-624.
36. Nagarkatti DG, McKeon BP, Donahue BS, Fulkerson JP. Mechanical evaluation of a soft tissue interference screw in free tendon anterior cruciate ligament graft fixation. *Am J Sports Med.* 2001;29:67-71.
37. Nevill AM, Holder RL, Stewart AD. Modeling elite male athletes' peripheral bone mass, assessed using regional dual x-ray absorptiometry. *Bone.* 2003;32:62-68.
38. Nordstrom P, Lorentzon R. Site-specific bone mass differences of the lower extremities in 17-year-old ice hockey players. *Calcif Tissue Int.* 1996;59:443-448.
39. Petersen W, Zantop T. Anatomy of the anterior cruciate ligament with regard to its two bundles. *Clin Orthop Relat Res.* 2007;454:35-47.
40. Prevrhal S, Fuerst T, Fan B, et al. Quantitative ultrasound of the tibia depends on both cortical density and thickness. *Osteoporos Int.* 2001;12:28-34.
41. Radford WJ, Amis AA. Biomechanics of a double prosthetic ligament in the anterior cruciate deficient knee. *J Bone Joint Surg Br.* 1990;72:1038-1043.
42. Sakane M, Fox RJ, Woo SL, Livesay GA, Li G, Fu FH. In situ forces in the anterior cruciate ligament and its bundles in response to anterior tibial loads. *J Orthop Res.* 1997;15:285-293.
43. Seil R, Rupp S, Krauss PW, Benz A, Kohn DM. Comparison of initial fixation strength between biodegradable and metallic interference screws and a press-fit fixation technique in a porcine model. *Am J Sports Med.* 1998;26:815-819.
44. Siebold R. Observations on bone tunnel enlargement after double-bundle anterior cruciate ligament reconstruction. *Arthroscopy.* 2007;23:291-298.
45. Siebold R, Dehler C, Ellert T. Prospective randomized comparison of double-bundle versus single-bundle anterior cruciate ligament reconstruction. *Arthroscopy.* 2008;24:137-145.
46. Siebold R, Ellert T, Metz S, Metz J. Femoral insertions of the anteromedial and posterolateral bundles of the anterior cruciate ligament: morphometry and arthroscopic orientation models for double-bundle bone tunnel placement—a cadaver study. *Arthroscopy.* 2008;24:585-592.
47. Siebold R, Ellert T, Metz S, Metz J. Tibial insertions of the anteromedial and posterolateral bundles of the anterior cruciate ligament: morphometry, arthroscopic landmarks, and orientation model for bone tunnel placement. *Arthroscopy.* 2008;24:154-161.

48. Siebold R, Thierjung H, Cafaltzis K, Hoeschlel E, Tao J, Ellert T. Tibial bone bridge and bone block fixation in double-bundle anterior cruciate ligament reconstruction without hardware: a technical note. *Knee Surg Sports Traumatol Arthrosc.* 2008;16:386-392.
49. Smith PA, Schwartzberg RS, Lubowitz JH. No tunnel 2-socket technique: all-inside anterior cruciate ligament double-bundle retroconstruction. *Arthroscopy*. 2008;24:1184-1189.
50. Takahashi M, Doi M, Abe M, Suzuki D, Nagano A. Anatomical study of the femoral and tibial insertions of the anteromedial and posterolateral bundles of human anterior cruciate ligament. *Am J Sports Med.* 2006;34:787-792.
51. Tetsumura S, Fujita A, Nakajima M, Abe M. Biomechanical comparison of different fixation methods on the tibial side in anterior cruciate ligament reconstruction: a biomechanical study in porcine tibial bone. *J Orthop Sci.* 2006;11:278-282.
52. Vogler HW. Basic bioengineering concepts: concepts in bone performance, failure, and osteosynthesis. *Clin Podiatry.* 1985;2:161-189.
53. Walsh MP, Wijdicks CA, Parker JB, Hapa O, LaPrade RF. A comparison between a retrograde interference screw, suture button, and combined fixation on the tibial side in an all-inside anterior cruciate ligament reconstruction: a biomechanical study in a porcine model. *Am J Sports Med.* 2009;37:160-167.
54. Weiss JA, Paulos LE. Mechanical testing of ligament fixation devices. *Tech Orthop.* 1999;14:14-21.
55. Yagi M, Wong EK, Kanamori A, Debski RE, Fu FH, Woo SL. Biomechanical analysis of an anatomic anterior cruciate ligament reconstruction. *Am J Sports Med.* 2002;30:660-666.
56. Yamanaka M, Yasuda K, Tohyama H, Nakano H, Wada T. The effect of cyclic displacement on the biomechanical characteristics of anterior cruciate ligament reconstructions. *Am J Sports Med.* 1999;27:772-777.
57. Yasuda K, Kondo E, Ichiyama H, et al. Anatomic reconstruction of the anteromedial and posterolateral bundles of the anterior cruciate ligament using hamstring tendon grafts. *Arthroscopy.* 2004;20:1015-1025.
58. Zantop T, Herbort M, Raschke MJ, Fu FH, Petersen W. The role of the anteromedial and posterolateral bundles of the anterior cruciate ligament in anterior tibial translation and internal rotation. *Am J Sports Med.* 2007;35:223-227.
59. Zantop T, Petersen W, Sekiya JK, Musahl V, Fu FH. Anterior cruciate ligament anatomy and function relating to anatomical reconstruction. *Knee Surg Sports Traumatol Arthrosc.* 2006;14:982-992.
60. Zantop T, Wellmann M, Fu FH, Petersen W. Tunnel positioning of anteromedial and posterolateral bundles in anatomic anterior cruciate ligament reconstruction: anatomic and radiographic findings. *Am J Sports Med.* 2008;36:65-72.
61. Zelle BA, Brucker PU, Feng MT, Fu FH. Anatomical double-bundle anterior cruciate ligament reconstruction. *Sports Med.* 2006;36:99-108.