

Compaction of a Bone Dowel in the Tibial Tunnel Improves the Fixation Stiffness of a Soft Tissue Anterior Cruciate Ligament Graft

An In Vitro Study in Calf Tibia

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Background: Despite increasing attention on fixation of a soft tissue anterior cruciate ligament graft in the tibia, there have been no studies on the use of a bone dowel as a joint line fixation device for promoting fixation properties, especially stiffness at the time of implantation.

Purpose: To determine whether compacting a bone dowel into the tibial tunnel improves fixation stiffness, yield load, and resistance to slippage of a soft tissue anterior cruciate ligament graft.

Study Design: Controlled laboratory study.

Methods: A double-looped tendon graft was fixed at the distal end of the tibial tunnel with a WasherLoc in 24 calf tibias. The tibial tunnels were treated with or without a dowel of cancellous bone. The bone dowel was harvested from the tibial tunnel and then compacted into a tapered space anterior to the anterior cruciate ligament graft as a joint line fixation device. A cyclic load and measurement test was administered to determine fixation stiffness, yield load, slippage, and failure mode.

Results: The specimens with the bone dowel had 58 N/mm more stiffness ($P = .04$); however, the yield load and resistance to slippage were similar in specimens with and without the bone dowel.

Conclusions: A bone dowel harvested from the tibial tunnel can be used as a joint line fixation device in series with a distal fixation method to improve initial fixation stiffness and increase the fit, which is known to enhance tendon graft-to-bone healing in the tibia.

Keywords: anterior cruciate ligament (ACL); graft healing; bone stiffness fixation

The keys to success in the reconstruction of an ACL are the initial mechanical fixation and rate of healing of the ACL graft in bone.^{27,29} The mechanical fixation provided by a fixation device must be greater for a soft tissue graft than for a bone plug graft because the healing rate in a tunnel of a soft tissue ACL graft is slower than that of a bone plug graft.³¹

Mechanical fixation and soft tissue graft-to-bone healing are especially problematic in the tibia because the tibia is

softer and more marrow dominated than is the femur.^{4,11,35} The softer cancellous bone in the tibia impairs the grip of fixation devices that primarily purchase cancellous bone, such as the interference screw.⁷ The marrow-dominated metaphysis slows soft tissue graft-to-bone healing.¹¹ Methods that improve the mechanical fixation and rate of healing of a soft tissue graft in the tibia should enable patients to be mobilized early and should restore better stability to the knee.²⁷

Several studies have emphasized the need to match the stiffness of the graft construct to that of the intact ACL.^{9,17} For the sake of clarity, we use the term *graft construct* to refer to the graft and the tibial and femoral fixation devices and the term *fixation stiffness* to refer to the stiffness of the fixation method without the graft. The best method for matching the stiffness of the graft construct to that of the intact ACL is with the use of a tibial and femoral device with high fixation stiffness.^{9,17,21,30} The use

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One or more of the authors has declared a potential conflict of interest as specified in the AJSM Conflict of Interest statement.

of a device with high fixation stiffness benefits the knee by lowering the initial tension needed to restore stability and protects the knee against a recurrence of instability.¹⁷

The location with respect to the joint line where a fixation device should be placed so that the graft construct has high stiffness is controversial. Several studies advocate fixation of a soft tissue ACL graft at the joint line with an interference screw to increase stiffness of the graft construct by shortening the graft.^{16,22,23,36,37} Other *in vivo* and *in vitro* studies have shown that the stiffness of the graft construct with a distal fixation device (ie, WasherLoc and Bone Mulch Screw, Arthrotek Inc, Warsaw, Ind) and tandem washers is even greater or at least similar to joint line fixation with a metal and bioabsorbable interference screw even though the graft is lengthened.^{19,21,29} One reason that the stiffness of the graft construct is high with a distal device is that the distal device provides purchase in cortical bone, which is stiffer and stronger than the cancellous bone purchased by an interference screw. Another reason that the stiffness of the graft construct is high with a distal device is that the stiffness of the graft construct is determined more by the fixation stiffness than by the stiffness (ie, length) of the graft, which is analogous to the strength of the graft construct being determined more by the fixation strength than by the strength of the graft.^{21,30}

A disadvantage of joint line fixation is that the healing rate of tendon graft to bone with an interference screw is slower than distal fixation because the interference screw blocks healing between the ACL graft and tunnel wall.^{29,34} In contrast, there is an advantage of distal fixation in that bone reamings compacted into the tunnel alongside the soft tissue ACL graft are used as a joint line fixation device to increase stiffness and tighten the fit.^{30,33} Tightening the fit and adding a bone graft improve the rate of soft tissue graft-to-bone healing.^{12,15}

The purpose of this study was to determine whether the technique of compacting a bone dowel in the tibial tunnel alongside a soft tissue ACL graft that is fixed distal to the joint line with a WasherLoc improves the initial fixation properties. The investigation of newer techniques to augment tibial fixation is needed because recent studies have shown that other methods such as tunnel compaction with serial dilators^{25,28} and compaction drilling^{24,26} do not improve the initial fixation properties of interference screws. We tested the hypothesis that a bone dowel increases fixation stiffness, increases yield load, and decreases slippage in the tibia by functioning like a joint line fixation device in series with a distal fixation device.

MATERIALS AND METHODS

Materials

Twelve pairs of calf knees (age, 16-24 weeks) were harvested at an abattoir and stored at -20°C . Calf knees were chosen for use in this study because the density of the proximal tibia closely approximates that of young human bone, according to a previously established model.^{14,35,36}

Preparation of the Double-Looped Bovine Tendon Graft

Bovine extensor tendon was used as the ACL graft because it is less expensive than is a human double-looped semitendinosus and gracilis graft, is free of communicable disease, and has similar structural properties when the cross-sectional area and length are matched.⁸ The ACL graft was prepared by cutting the extensor tendon to a length of 27 cm and dividing the tendon along the bifurcation into 2 strands. Placing the 2 strands side by side and folding the strands into a loop formed the double-looped bovine tendon (DLBT) graft. The cross-sectional area of the graft was trimmed until the graft fit through a 9- but not an 8-mm-diameter sizing sleeve (Arthrotek Inc). The cross-sectional area of the graft was determined by averaging measurements made with an area micrometer 15, 45, and 75 mm from the loop.⁸

Determination of Stiffness of the DLBT Graft

The stiffness of each DLBT graft was computed from a load-displacement test administered by a computer-controlled materials testing machine (Teststar IIs, v2.2 [software], Model 858, MTS Systems Corporation, Minneapolis, Minn) with a 5-kN load cell (1010AF-1K-B, Interface, Scottsdale, Ariz) using a previously described technique.⁸ Briefly, the DLBT graft was looped over a 6.3-mm-diameter steel bar attached to the base of the materials testing machine. The strands were tensioned equally by tying a 1.0-kg weight to each strand and hanging each weight over a pulley.⁸ A liquid nitrogen freeze clamp bolted to the shaft of the actuator gripped the strands. The grip-to-grip length of the DLBT graft was 95 mm. The graft was cycled 11 times between 20 and 1000 N at 400 N/s. The first 10 cycles preconditioned the graft. Stiffness was computed from the load-displacement curve obtained during the 11th cycle.

Preparation of Tibial Tunnel and Harvest of Bone Dowel

The calf knee was thawed overnight at room temperature. The tibia was removed, and the shaft was cut 20 cm distal to the proximal articulating surface. The diaphysis was cemented in an aluminum cylinder 6.4 cm in diameter and 10 cm in length. With use of a previously described technique, the aluminum cylinder was clamped in a jig that facilitated drilling of the tibial tunnel, tensioning the DLBT graft, and inserting the fixation device.²

The tibial tunnel was positioned with a drill guide (Howell Tibial Guide, Arthrotek Inc). The tip of the guide was centered between the medial and lateral tibial eminence. The drill sleeve was positioned on the medial tibia equidistant from the anterior and posterior cortex and set at a length of 40 mm. A 2.4-mm K-wire was drilled across the tibia. A 9-mm cannulated reamer, which matched the diameter of the DLBT graft, was used to remove the distal cortex of the tibial tunnel. A cannulated plunger was inserted into a harvesting tube with an 8.0-mm outside

and 7.0-mm inside diameter, and a handle was attached to the harvesting tube bone. The harvesting tube and plunger were impacted over the guide wire to subchondral bone (Figure 1). The harvesting tube was rotated clockwise and counterclockwise several times to break the tip of the cancellous dowel from the subchondral bone. The harvesting tube was removed from the tunnel. The handle was removed, and the length of the bone dowel was measured from the length the plunger extended from the harvesting tube. The drilling of the tibial tunnel was completed with the 9-mm cannulated reamer. A 17-mm-diameter recess to countersink the distal fixation device (WasherLoc, Arthrotek Inc) was drilled into the distal end of the tibial tunnel with a counterbore (Counterbore, Arthrotek Inc).

Insertion of Distal Tibial Fixation Device

The DLBT graft was looped around a steel bar attached to the jig, and the strands were passed through the tibial tunnel. The jig was adjusted until the length between the articular surface and the steel bar was 55 mm. The strands of the DLBT graft were tensioned equally by tying a 1.0-kg weight to each strand and hanging the weight over a pulley. The WasherLoc was inserted with use of a previously described technique.²¹ Briefly, the WasherLoc was threaded on the awl, and the awl was inserted in the hole created by the counterbore. One strand from each tendon was placed on opposite sides of the awl, and the spikes of the WasherLoc were driven into cortical bone with a mallet. A 3.2-mm hole was drilled through the lateral tibial cortex, and a 6.5-mm-diameter self-tapping cancellous screw was inserted through the WasherLoc to tighten and compress the DLBT graft.

Insertion of Bone Dowel

A computer-generated randomization protocol was used to determine whether a tibia was treated with the bone dowel. With the DLBT graft fixed in the tibia with the WasherLoc, a cone-shaped dilator that tapers from 3 to 8 mm was driven 25 mm into the tibial tunnel anterior to the graft to the level of the joint line (Figure 2). A plastic cap was placed over the cutting tip of the harvester, and the harvester was centered over the dilated opening. The plunger on the harvester was struck firmly with a mallet, which compacted the bone dowel into the dilated space.

Testing the Graft Construct

The graft construct was tested with use of a previously described technique.² Briefly, the aluminum cylinder containing the tibia was clamped in a 6 degrees of freedom fixture bolted to the actuator of the materials testing machine (Figure 3). The axis of the tibial tunnel was aligned with the shaft of the actuator by adjusting the fixture. The graft was looped around a steel bar bolted to the base of the materials testing machine. Two linear variable displacement transducers (LVDTs) were placed close to the lateral and medial side of the tibia to measure local displacement of the graft construct. The graft construct

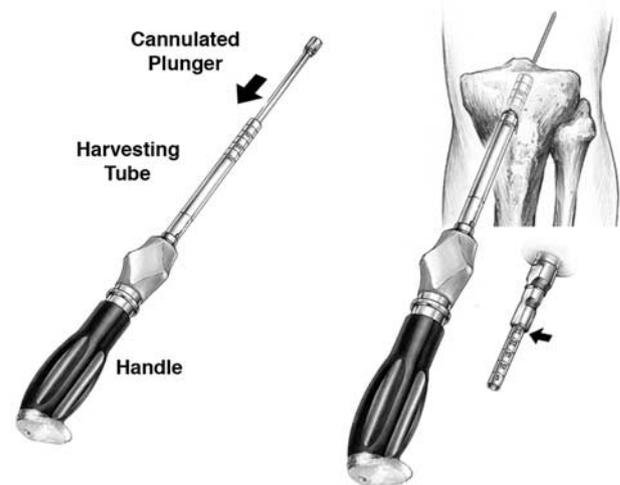


Figure 1. The cannulated plunger is inserted into the harvesting tube (left). The harvesting tube is attached to a handle through a quick-coupling collet. The cannulation in the plunger centers the harvesting tube over the tibial tunnel guide wire. The distal tibial cortex is removed with a cannulated reamer that matches the diameter of the graft. The harvesting tube and plunger are driven with a mallet over the tibial tunnel guide wire to subchondral bone (right). The harvesting tube containing the bone dowel is removed from the tunnel. The reamer is used to drill through the subchondral bone. The handle is detached from the harvesting tube, which reveals the calibrated end of the plunger (inset right). The length the plunger extends from the proximal end of the harvesting tube determines the length of the bone dowel (arrow).

was not preconditioned before tensile testing to replicate the surgical technique of inserting an ACL graft. Preconditioning of the graft–fixation device–tibia complex is not a surgical step and would have underestimated slippage and made our findings clinically irrelevant. The gauge length was established by applying a 10-N tare load. A cyclic load and measurement test was administered as follows. A tensile load of 50 N was applied to the graft construct at 400 N/s, the tension was lowered to 10 N, and the displacement of the graft construct was determined by averaging the displacement of the 2 LVDTs. This cycle of loading the construct and measuring displacement was repeated after progressively increasing the tensile load in 50-N increments until the graft construct failed. The worst-case error of each LVDT was 0.125 mm, based on the full-scale range of 5 cm and the nonlinearity of the full-scale range of 0.25%. Because 2 LVDTs were used, and because the measurements from both LVDTs were averaged to calculate displacement, the worst-case error of the calculated displacement was 0.125 mm.

Determination of Mode of Failure

The mode of failure was categorized into 1 of 3 categories. The graft slipping from under the fixation device without a visible change in the position of the fixation device was

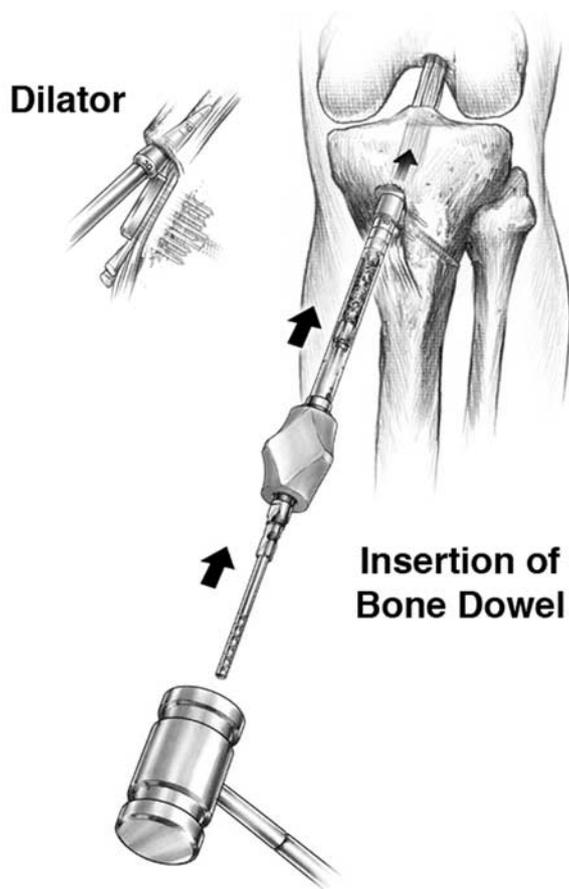


Figure 2. The tapered dilator is inserted into the tibial tunnel anterior to the soft tissue ACL graft and WasherLoc and driven with a mallet 25 mm to the level of the joint line, which creates a cone-shaped space by driving the dilator (upper left). The tip of the harvester tube is covered with a plastic cap to prevent cutting the graft and is positioned over the dilated opening. The plunger is struck by a mallet until the cylindrical-shaped cancellous bone dowel is compacted into the cone-shaped space (lower right).

graft pullout. The graft tearing from under the fixation device without a visible change in the position of the fixation device was graft rupture. A visible change in the position of the fixation device without slippage or tearing of the graft was bone fracture.

Data Reduction and Statistical Analysis

The fixation stiffness, yield load, and slippage of the graft construct were computed using a previously described technique.² The fixation stiffness (K_F) (ie, bone dowel and WasherLoc, or WasherLoc alone) was calculated based on an equation of a springs-in-series model, which was previously described.^{21,30} For each specimen, the fixation stiffness was calculated using the equation $K_F = K_{GC} \times K_G / (K_G - K_{GC})$, and the values we determined for graft stiffness (K_G) and stiffness of the graft construct (K_{GC}).^{21,30}

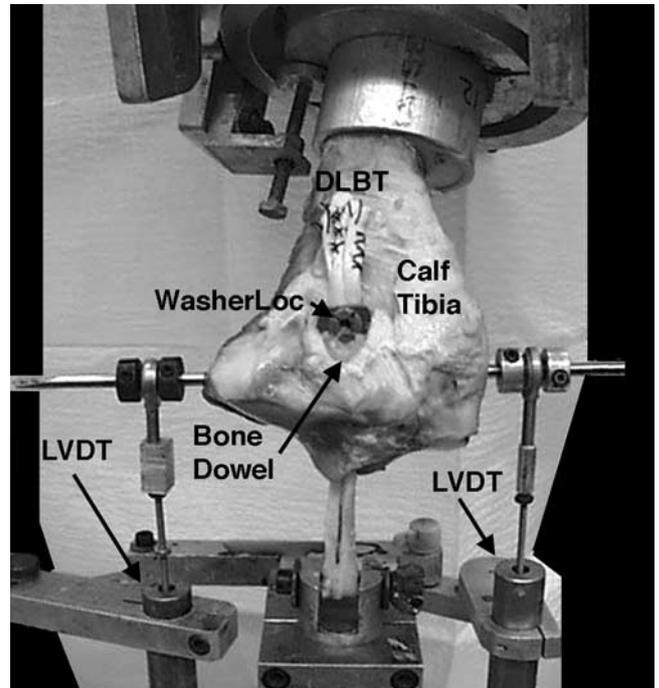


Figure 3. The testing setup is shown with the components labeled. The 6 degrees of freedom fixture (top) is attached to the actuator of the materials testing machine (not shown). The shaft of the calf tibia is potted in an aluminum cylinder with bone cement and clamped in the fixture. The double-looped bovine tendon (DLBT) graft is looped around a steel bar bolted to the base of the testing machine, passed through a tibial tunnel, and fixed with the WasherLoc and, in this specimen, a bone dowel. Displacement between the tibia and the looped end of the DLBT graft is measured with 2 linear variable displacement transducers (LVDTs). Each LVDT (accuracy of ± 0.125 mm) is positioned close to the medial and lateral side of the tibia and attached to a transfixion pin drilled across the tibia just distal to the joint line. Displacement of the graft construct is the average of the displacement measured by the 2 LVDTs.

The data concerning whether the bone dowel increased fixation stiffness, increased yield load, and decreased slippage of the tibial fixation method were analyzed with use of an unpaired *t* test (SAS release 8.0, SAS Institute, Cary, NC). The data concerning whether the bone dowel changed the mode of failure were analyzed with use of a chi-square test. The level of significance was set at $P < .05$.

RESULTS

Fixation Properties

Compaction of a bone dowel in the tibial tunnel increased the fixation stiffness 58 N/mm ($P = .04$) but had no effect on the yield load ($P = .687$) and slippage at 500 N of tensile load ($P = .670$) (Table 1).

TABLE 1

The 3 Fixation Properties of Fixation Stiffness, Yield Load, and Slippage at 500 N of Tensile Load for a DLBT Graft^a

Type of Tibial Fixation (Species of Bone)	Fixation Properties		
	Fixation Stiffness, N/mm	Yield Load, N	Slippage at 500 N, mm
Bone dowel and WasherLoc (calf)	565 ± 63	1098 ± 148	1.1 ± 1.7
WasherLoc only (calf)	507 ± 74	1070 ± 208	1.1 ± 2.1
WasherLoc only (young human) ^b	506 ± 197	905 ± 291	1.9 ± 1.3
WasherLoc only (porcine) ^b	429 ± 269	903 ± 178	0.8 ± 0.6
<i>P</i>	.04	.687 (NS)	.670 (NS)

^aData reflect the fixation properties for a double-looped bovine tendon (DLBT) graft with distal fixation in a calf tibia (ie, WasherLoc), treated with or without a dowel of cancellous bone. Statistical tests were made between the measurements in calf tibia only. NS, not significant.

^bFor comparison, data in young human and porcine tibia are included from a previous study.²²

Failure Mode

All the specimens treated with or without the bone dowel failed by graft pullout ($P = 1.000$).

DISCUSSION

The overall objective of the study was to determine whether the compaction of a dowel of cancellous bone into the tibial tunnel alongside a soft tissue ACL graft improves the fixation properties in calf tibia. We found that a bone dowel increases stiffness by functioning like a joint line fixation device in series with a distal fixation device. Before discussing the clinical implications of these observations, a methods issue should be reviewed.

Methods Issue

A methods issue of our study is whether the increase in stiffness from the use of a bone dowel was overestimated because calf tibia was used instead of young human tibia. Fresh proximal calf tibia (age, 16-24 weeks) was used in this study because calf proximal tibia closely approximates the density of young human bone, according to a previously reported model.^{14,35,36} In our study, the increase in stiffness of 58 N/mm from compacting a bone dowel in the tibial tunnel in calf bone was similar to the reported increase in stiffness of 41 N/mm from compacting bone reamings in the femoral tunnel in young human bone.³⁰ The stiffness of the fixation method (507 ± 74 N/mm) in calf bone with the WasherLoc in our study was identical to the stiffness of the fixation method (506 ± 197 N/mm) reported in young human bone with the WasherLoc (Table 1).²¹ Therefore, the increase in stiffness of 58 N/mm from inserting a bone dowel in calf tibia is probably a reasonable estimate of the increase in stiffness of a bone dowel in humans.

Interpretation and Significance of Results

The most important clinical application of our study is that a bone dowel, harvested from the tibial tunnel, can be used as a supplemental joint line fixation device in series with a distal fixation device in the tibia to increase the stiffness of a soft tissue ACL graft at the time of implantation. The findings from our study and others do not support the opinion that a soft tissue graft must be fixed at the joint line to stiffen the graft construct. Collectively, these studies have shown that distal fixation in the tibia with either the WasherLoc or tandem washers alone provides greater or at least similar stiffness to joint line fixation with a wide variety of metal and bioabsorbable interference screws, even though the graft is lengthened with distal fixation.^{18,19,21,29,30} The compaction of a bone dowel further increases the fixation stiffness of a distal device. Therefore, the surgeon interested in a stiff graft construct can use a bone dowel in series with a distal device of high fixation stiffness (ie, WasherLoc, tandem washers) instead of joint line fixation with an interference screw.

The use of a supplemental fixation device in series with a primary fixation device is a concept that has been studied with interference screw fixation of a soft tissue graft.^{1,13,38} The EndoPearl device (Linvatec, Largo, Fla) was designed to improve the fixation properties of the interference screw by adding a supplemental fixation device at the distal end of the graft. Biomechanical studies have shown that the addition of an EndoPearl device distal to an interference screw fixation increases stiffness (26-42 N/mm), increases yield load (386-659 N), and decreases slippage.³⁸ In contrast to the EndoPearl device, the addition of bone dowel fixation to WasherLoc fixation only increased stiffness and did not increase the yield load or decrease slippage under cyclic load. However, the increase in stiffness from compacting a bone dowel into the tibial tunnel (58 N/mm) is substantial because the bone dowel provides 16 N/mm more stiffness than does an EndoPearl device (42 N/mm).³⁸

Fixation techniques that promote tendons to heal faster in a tunnel are especially important for those surgeons who are used to the fast healing of a bone plug (ie, bone–patellar tendon–bone graft) in a tunnel because it takes 6 weeks for the healing of a soft tissue graft to equal that of a bone plug graft.³¹ Studies have shown that tendon tunnel healing is promoted by (1) lengthening the tunnel,¹² (2) tightening the fit in the tunnel,¹² (3) providing circumferential contact between the graft and tunnel (ie, no interference screw),²⁹ and (4) inserting a biologically active substance in the tunnel.^{6,20} The use of a cancellous bone dowel with a distal fixation device fulfills these 4 conditions for promoting tendon tunnel healing.

Without a clinical trial, we are unable to state whether the use of a bone dowel in the tibial tunnel will speed tendon tunnel healing. However, if the use of a bone dowel speeds tendon tunnel healing, and as tendon tunnel healing is generally considered the rate-limiting step in rehabilitation and return to sports, then the use of a bone dowel might allow a safer and earlier return to exercise and sports.

Revision surgery should be easier with a bone dowel and distal fixation device than with an interference screw because the bone defect in the tibia is smaller. The use of a bone dowel shrinks the tunnel by filling voids between the tendon graft and tunnel,³⁰ and the use of a distal fixation device does not enlarge the tunnel as does the use of an interference screw.⁵ The technique described in this study to bone graft the tibial tunnel has been in clinical use since 2002. The technique consists of 3 simple steps: harvesting, dilating, and inserting the bone dowel. These extra steps require only 1 to 2 minutes of additional surgical time. The technique is relatively economical because autogenous bone is used instead of allograft bone. The only expense is the cost of the disposable harvester tube.

On occasion, the bone dowel may be shorter than the desired length of 25 mm. In this case, we increase the length of the bone dowel by removing the plunger from the harvesting tube and filling the tube with reamings from the tibial and femoral tunnel and remnants from the wall and roofplasty (H. Freedberg, MD, oral communication, January, 2004). To date, we have not observed any portion of the bone dowel inside the knee joint. The taper of the dilated space contains the dissimilar cylindrical-shaped bone dowel inside the tibia during compaction. Although we are in the process of quantifying the fill of the tunnel by the bone dowel, qualitative evaluation of postoperative radiographs clearly showed a tunnel that is tapered and smaller than the diameter of the reamer used to drill the tibial tunnel (Figure 4).

Although an allograft bone dowel was not evaluated in this study, the increase in stiffness from the use of an allograft bone dowel should be similar to an autogenous bone dowel. However, the disadvantages of an allograft dowel are that allograft bone is slower to incorporate than is autograft bone,¹⁰ has a risk of disease transmission,^{3,32} and costs more.

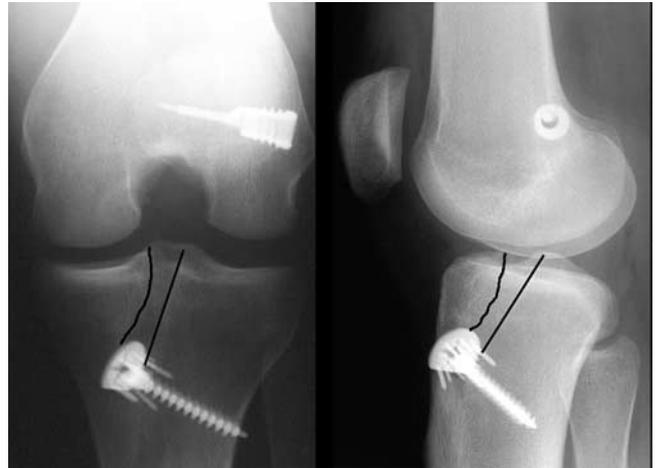


Figure 4. Notch (left) and lateral (right) radiographs taken 4 months after an ACL reconstruction with a double-looped semitendinosus and gracilis graft showing shrinkage of the tibial tunnel with a cancellous bone dowel. The ACL graft was fixed inside the distal end of the tibial tunnel with a WasherLoc and a cancellous compression screw. The concave lines outline the dilated side of the tibial tunnel and the location of the bone dowel. The straight lines outline the undilated wall of the tunnel. Shrinkage is seen in the notch view on the medial side of the tibial tunnel and in the lateral view on the anterior side of the tibial tunnel.

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