

Does a Tensioning Device Pinned to the Tibia Improve Knee Anterior–Posterior Load-Displacement Compared to Manual Tensioning of the Graft following Anterior Cruciate Ligament Reconstruction? A Cadaveric Study of Two Tibial Fixation Devices

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ABSTRACT: Devices that are pinned to the tibia to tension an anterior cruciate ligament (ACL) graft produce joint reaction loads that in turn can affect the maintenance of graft initial tension after tibial fixation and hence knee anterior–posterior (AP) load-displacement. However, the effect of these devices on AP load-displacement is unknown. Our objectives were to determine whether tensioning by device versus tensioning by hand causes differences in AP load-displacement and intraarticular graft tension for two commonly used tibial fixation devices: a bioresorbable interference screw and a WasherLoc. AP load-displacement and intraarticular graft tension were measured in 20 cadaveric knees using a custom arthrometer. An initial tension of 110 N was applied to a double-looped tendon graft with the knee at extension using a tensioning device pinned to the tibia and a simulated method of tensioning by hand. After inserting the tibial fixation device, the 134 N anterior limit (i.e., anterior position of the tibia with respect to the femur with a 134 N anterior force applied to the tibia) and 0 N posterior limit (i.e., AP position of the tibia relative to the femur with a 0 N force applied to the tibia) were measured with the knee in 25° flexion. Intraarticular graft tension was measured at extension. These limits and intraarticular graft tension were also measured after cyclically loading the knee 300 times. Compared to a simulated method of tensioning by hand, tensioning with a device pinned to the tibia did not decrease the 134 N anterior limit and did not cause posterior tibial translation. However, intraarticular graft tension was maintained better with a tensioning device pinned to the tibia for the Washerloc, but not the interference screw. For two commonly used tibial fixation devices, a tensioning device pinned to the tibia does not improve AP load-displacement at 25° flexion over tensioning by hand when the graft is tensioned at full extension, but does improve the maintenance of intraarticular graft tension for the Washerloc. © 2006 Orthopaedic Research Society. Published by Wiley Periodicals, Inc. *J Orthop Res* 24:1832–1841, 2006

Keywords: anterior cruciate ligament; graft; tensioning; anterior stability; joint reaction load; laxity

INTRODUCTION

The method used to tension an anterior cruciate ligament (ACL) graft can produce joint reaction loads that in turn can affect knee anterior-posterior (AP) load-displacement of the reconstructed knee. One method for graft tensioning that produces joint reaction loads in addition to the gravity effect of the shank-foot is the use of a mechanical device pinned to the tibia (Fig. 1A). In contrast, the commonly used method of graft

tensioning by hand^{1–3} does not produce additional joint reaction loads (Fig. 1B). The AP load-displacement of the reconstructed knee may depend on the tensioning method, so how these two methods affect knee AP load-displacement is a question of clinical importance.

To appreciate the relationship between joint reaction loads and AP load-displacement, it is useful to consider each tensioning method in turn. Pinning a device to the tibia and tensioning the graft with the knee in full extension produces a combination of joint loads, including primarily a compressive force on the articular surface and a posterior force on the tibia (Fig. 1A). For example, with the knee in extension and an initial graft

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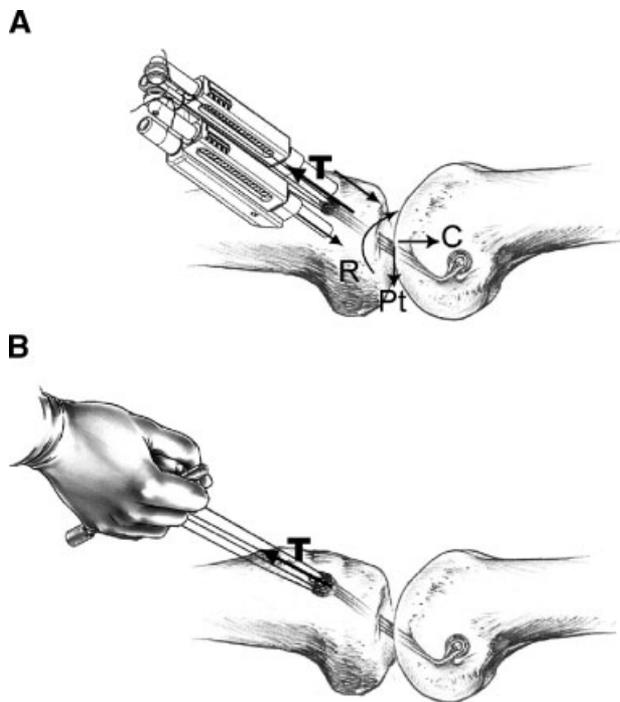


Figure 1. Diagram showing the method of a tensioning device pinned to the tibia, which produces joint reaction loads (top drawing), and the method of tensioning of the graft by hand, which does not produce joint reaction loads (bottom drawing). When using the tensioning device, the tension applied by the device (T) primarily produces three joint reaction loads, which include a compressive force on the articular surface of the knee (C), a posterior force on the tibia (Pt), and an external axial moment on the tibia (R).

tension of 110 N, the compressive and posterior forces are about 100 and 40 N, respectively. Because the posterior force could cause posterior tibial subluxation, the knee AP load-displacement could be affected because the initial graft tension would be maintained as a result of resistance by the posterior structures.

In tensioning by hand, the lack of any joint reaction loads is potentially problematic to the AP load-displacement of the reconstructed knee. Although this method develops tension in the graft, the posterior structures do not resist this tension. Assuming that inserting the tibial fixation device does not create joint reaction loads, the tibia is free to move posteriorly when the graft is released after fixation; the initial tension would not be maintained and AP load-displacement might be lost.

Inserting the tibial fixation device adds an additional complexity in assessing how either method will affect AP load-displacement. Addi-

tional joint reaction forces will be developed depending on the type of device that is inserted. If these reaction forces are low compared to the joint reaction forces developed by the tensioning device, then the latter forces will dominate. In that case, the AP load-displacement might be better for tensioning by device. However, if the forces developed by inserting the device are high compared to the forces developed by the tensioning device, then the AP load-displacement might be similar for the two methods.

The primary objective of our study was to determine whether tensioning by device versus tensioning by hand causes differences in knee AP load-displacement for two commonly used tibial fixation devices. To interpret any differences in knee stability between the two tensioning methods, a secondary objective was to measure the intra-articular graft tension.

MATERIALS AND METHODS

Preparation of the Intact Knee

Twenty cadaveric knees (average age, 75 years, range 56 to 89 years) were harvested and stored at -20°C . Radiographs and visual inspection during ACL reconstruction showed no moderate or severe degenerative arthritis, chondrocalcinosis, or torn menisci. The knee was thawed overnight. All soft tissue was removed 7 cm distal and proximal from the joint line. The femoral and tibial diaphyses were cut 20 cm from the joint line, and a 12.7 mm diam steel rod was cemented inside each medullary canal to within 7.5 cm of the joint line. The femoral diaphysis was cemented in a 6.4 cm diameter, 22 cm long aluminum cylinder, 6.5 cm proximal to the joint line.

The knee was placed supine in a testing apparatus that permitted unconstrained knee motion from 30° of flexion to hyperextension. The apparatus was designed and built in our laboratory, and was used for tensioning the graft, inserting each tibial fixation device, measuring the knee AP displacement, and cyclically loading the knee (Fig. 2). The aluminum cylinder containing the femur was clamped in the femoral fixture, with the flexion-extension axis of the knee perpendicular to the sagittal plane. Motion of the tibia was unconstrained by attaching a low-friction bearing to the end of the steel rod extending from the tibia and resting the bearing on a low-friction Delrin plate. The length, ankle height, weight, and center of gravity of the tibia were set to that of the shank-foot complex of an 81-kg, 180-cm male based on anthropometric measurements.⁴⁻⁶ Applying blocks of different height under the low-friction bearing set the flexion angle at either full extension or 25° of flexion. Manual extension until resistance was felt defined full extension.⁷ Knee flexion was measured with a goniometer ($\pm 1^{\circ}$ accuracy).

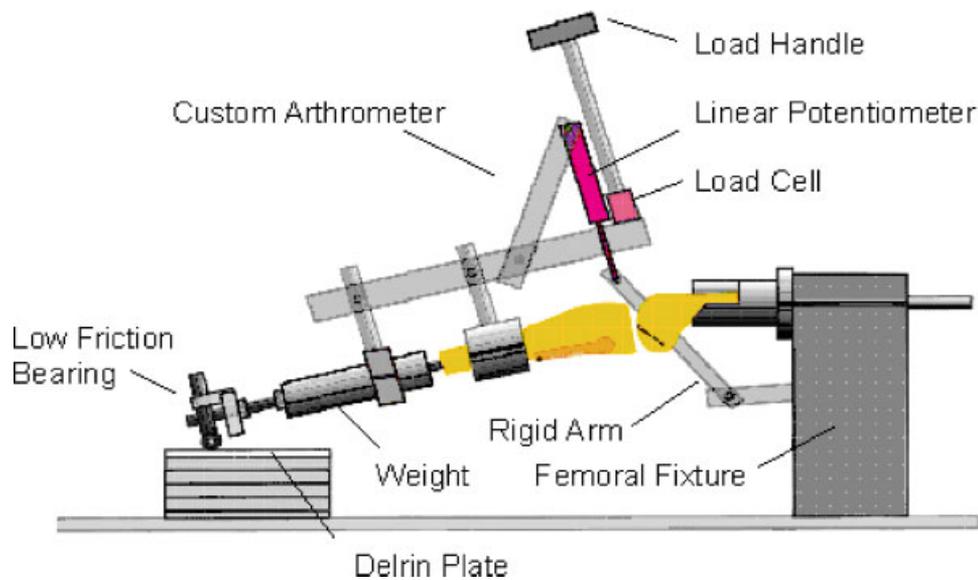


Figure 2. Diagram showing the knee in 25° of flexion in the testing apparatus. The rigidly fixed femur was aligned so that the flexion-extension axis was perpendicular to the sagittal (i.e., vertical) plane. The origin of the tibial coordinate system was the point where the longitudinal tibial axis (defined by the axis of the intramedullary rod) intersected a line perpendicular to the longitudinal tibial axis at the joint line and lay in the sagittal plane. The line in the sagittal plane and perpendicular to the longitudinal tibial axis at the joint line was the AP axis. The custom-made arthrometer was installed on the tibia with the load handle centered over the knee. Anterior and posterior forces were applied by pulling and pushing on the load handle. A load cell in series with the handle recorded the load. AP translation was measured with a linear potentiometer (ETI Systems, Carlsbad, CA) connected to a rigid arm, which was connected to the femoral fixture. The linear potentiometer was positioned above the tibia so that its axis was collinear with the AP axis. The linear potentiometer was connected through spherical bearings at both ends so that it did not constrain the motion of the knee. [Color scheme can be viewed in the online issue, which is available at <http://www.interscience.wiley.com>]

Measurement of the AP Displacement of the Intact Knee

The AP displacement of the intact knee at 25° of flexion in response to a 134-N anterior force applied perpendicular to the longitudinal axis of the tibia and in the sagittal plane was determined with a custom-made arthrometer using the loading protocol of a commercial arthrometer (KT-1000, MEDmetric Corp., San Diego, CA) (Fig. 2). An 89-N posterior force was applied to the tibia three times. The removal of the force after the third application defined the 0-N posterior limit of the tibia (i.e., position of the tibia relative to the femur with no force applied to the arthrometer). The 134-N anterior limit was the mean position of the tibia in response to three applications of 134-N anterior force. Applied forces were monitored in real time, and were within ± 1 N of the target value.

Preparation of the Double-Looped Tendon Graft

Forty double-looped tendon grafts were made from bovine extensor tendon,⁸ which has structural properties similar to those of a young human double-looped semitendinosus and gracilis graft.⁹ The tendons were trimmed in width until when looped over a suture they

passed snugly through a 9 mm-diameter cylinder, but not through an 8 mm-diameter cylinder (Sizing Sleeve, Arthrotek, Inc., Warsaw, IN). Four centimeters of the end of each strand were whip stitched using a No.1, braided, absorbable suture (Polysorb, United States Surgical/Syneture, Norwalk, CT).⁸

Technique of ACL Reconstruction

The tibial metaphysis was reinforced with polyurethane foam to provide fixation properties in elderly cadaveric tibia similar to those in young human tibia.⁸ The ACL was excised, and tibial and femoral drill holes were made using a transtibial technique¹⁰ that positions the graft without roof and PCL impingement and with a tension pattern during passive flexion-extension similar to that of the intact ACL.¹¹ The tibial tunnel was drilled to 8 mm in diameter and serially dilated to 9 mm. An open-end femoral tunnel was drilled to 16 mm diameter. The blowout of the posterior wall of the femoral tunnel was later closed with bone cement. A low-friction femoral bushing with an outer 16-mm diameter was machined from Delrin. A 9 mm-diameter tunnel was drilled in the center of the bushing from

distal to proximal to a depth of 10 mm. From the opposite end of the bushing, a 12.5 mm-diameter tunnel was drilled that stopped at the 9-mm diameter. The bushing was inserted into the femoral tunnel until flush with the intercondylar roof and fixed with bone cement. The femoral fixation device was made to slide with low friction in the 12.5 mm-diameter section of the bushing.¹⁰ A crossbar (2.4-mm diameter, 10-mm length) was welded to the distal end of the femoral fixation device to fix the ACL graft.

Each knee's treatment was randomly assigned to a tensioning device pinned to the tibia or a simulated method of tensioning by hand using a computer generated randomization protocol.

Technique of Pinning the Tensioning Device to the Tibia

In the knees treated with the tensioning device pinned to the tibia (SE Graft Tensioner, Linvatec Corp, Largo, FL), the graft was fixed to the tibia first with the interference screw and then with the WasherLoc, because this testing sequence minimizes carryover effects.^{8,10} The positions of the pins securing the tensioning device to the tibia were modified for each fixation device. For the interference screw, the two guide pins (SE™ Graft Tensioner Breakaway Pins, Linvatec Corp.) were placed through a drill guide (SE™) that was inserted flush against the distal end of the tibial tunnel. Because in a pilot study some pins lost purchase during tensioning, the bone surrounding each pin placement was overdrilled with a 6-mm reamer and reinforced with bone cement.

The knee was replaced in the testing apparatus. A double-looped tendon graft was selected at random for each test and was looped over the cross bar of the femoral fixation device. The femoral fixation device and graft were inserted into the femoral tunnel and connected to a turnbuckle that was connected to the base plate of the apparatus. The turnbuckle was adjusted so that the crossbar was positioned 20–25 mm inside the femoral bushing. Each graft strand was shortened and re sewn so that only 5 mm of tendon extended beyond the distal end of the tibial tunnel. The suture-separator device (SE™) and then the tensioning device were placed over the two guide pins positioned for the interference screw (Fig. 3). The sutures attached to each graft strand were routed divergently around the suture-separator device to allow subsequent concentric insertion of the interference screw. The sutures from the two strands belonging to the same tendon were tied together to form a closed loop. The two suture loops were each wrapped around one of two pulleys connected to a spring and turnbuckle on the tensioning device.

The knee was placed in full extension, and the turnbuckles of the tensioning device were adjusted until a tensile force of 75 ± 1 N was applied to each tendon, which produced a preconditioning graft tension¹² of 150 N. The reconstructed knee and graft were preconditioned by flexing and extending the knee between 20° of flexion and full extension until the

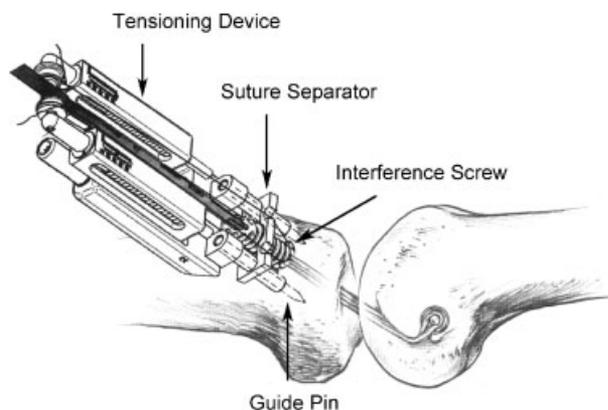


Figure 3. Diagram showing the application of the suture separator and tensioning device over the two guide pins with the knee in full extension. The sutures attached to each graft strand diverged around the suture-separator device to allow subsequent concentric insertion of the interference screw. The sutures from the two strands belonging to the same tendon were tied together to form a closed loop. The two loops of suture were each wrapped around a pulley connected to the spring and turnbuckle of the tensioning device. The turnbuckles of the tensioning device were adjusted until a tensile force of 55 ± 1 N was applied to each loop, which created an initial tension of 110 N in the graft.

change in graft tension was ≤ 1 N on five consecutive flexion-extension cycles. The knee was again placed in full extension, and the tension on each tendon adjusted to 55 ± 1 N, for an initial tension in the graft of 110 N. This value of initial tension restores the 134 N anterior limit to within ± 0.5 mm of that of the intact knee for the two fixation devices.¹⁰ A 1 mm-diameter guide wire (BioScrew® Hyperflex Guidewire, Linvatec Corp.) was inserted into the tibial tunnel through the center of the four graft strands. A 10 mm-diameter, 35-mm long interference screw (BioScrew® XtraLok, Linvatec Corp.) was advanced over the guide wire until flush with the distal cortex of the tibial tunnel. The guide wire and tensioning device were removed. The knee was placed at 25° flexion and the 0 N posterior limit and 134-N anterior limit were measured.

The fixation and graft were cyclically loaded by applying 300 load cycles between a posterior load of 26 N and an anterior load of 100 N with the arthrometer with the knee in 25° flexion. A pilot study ($N = 3$) showed that the change in 134-N anterior limit after 240 cycles was minimal. The application of 100 N through the arthrometer handle was used because the resulting graft tension is 170 N,¹⁰ the predicted maximum tension in the intact ACL during level walking.¹³ The 0-N posterior and 134-N anterior limits were measured after the 300th cycle. The tensioning device, interference screw, and double-looped tendon graft were removed.

For testing the reconstructed knee with WasherLoc fixation, a 17 mm-diameter counter bore was drilled into

the distal end of the tibial tunnel as previously described.^{8,10} The two guide pins were moved 10 mm distally. A new double-looped tendon graft was inserted, and the knee was replaced in the testing apparatus. The tensioning device was placed over the guide pins; the suture-separator device was not used. The double-looped tendon graft was attached to the springs, the graft was tensioned, and the graft and knee were preconditioned as previously described. The knee was placed in full extension, and the initial graft tension was set to 110 N. The WasherLoc was threaded on a drill sleeve, and the drill sleeve was threaded on an awl. The WasherLoc was positioned in the hole created by the counter bore, and one strand from each tendon was placed on opposite sides of the awl. Striking the awl with a mallet drove the WasherLoc into bone within the counter bore. A 6.5 mm-diameter self-tapping cancellous screw was inserted through the WasherLoc and tightened to fix the graft. A bone dowel harvested from a bovine tibia was placed inside the tibial tunnel.¹⁴ The 0-N posterior and 134-N anterior limits were measured after the knee was adjusted to 25° of flexion and after the 300th load cycle.

Method for Simulating Tensioning by Hand

With the simulated method of tensioning by hand, the reconstructed knee was tested first with interference screw and then with the WasherLoc to reduce carryover effects.^{8,10} The tensioning method relied on two tibial load cells (225 N, SM-50, Interface, Scottsdale, AZ) that were each connected to a pneumatic cylinder (Model No.

4CRAX-1-BC, Illinois Pneumatics, Rosco, IL) (Fig. 4). The pneumatic cylinders were mounted on a fixture connected to the base plate of the testing apparatus proximal to the knee so that tensioning the graft did not produce any joint reaction forces other than the weight of the shank-foot.

For testing the reconstructed knee with an interference screw, the sutures were routed around a custom suture-separator device that was placed over two guide pins inserted in the tibia in bone cement using the technique previously described. A new double-looped tendon graft was inserted, and the knee was replaced in the testing apparatus. The double-looped tendon graft was shortened and resewn so that 5 mm of each graft strand extended beyond the distal end of the tibial tunnel. The double-looped tendon graft was attached to the load cells, the graft was tensioned, and the graft and knee were preconditioned as previously described. The knee was placed in full extension and the tension in the graft was set to 110 N. A tensile force of 55 ± 1 N was applied to each load cell, for an initial tension of 110 N applied to the graft. The interference screw was inserted concentrically. The 0-N posterior and 134-N anterior limits were measured after the knee was adjusted to 25° of flexion and after the 300th load cycle. For testing the reconstructed knee with the WasherLoc, the previously described protocol was repeated without the custom suture-separator device. The 0-N posterior and 134-N anterior limits were again measured after the knee was adjusted to 25° of flexion and after the 300th load cycle.

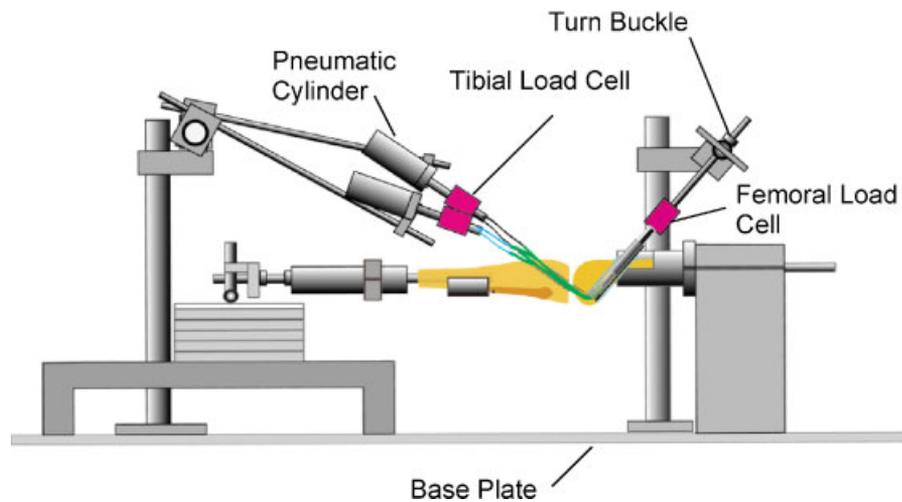


Figure 4. Diagram showing the method of simulating the tensioning of the graft by hand in the testing apparatus. The pneumatic cylinders were mounted on the base plate of the testing apparatus, not on the tibia, so that tensioning the graft did not produce any joint reaction loads. The sutures from the two strands belonging to the same tendon were tied together to form a closed loop. Each loop of suture was wrapped around a hook attached to the distal end of a pneumatic cylinder. With the knee in full extension, the tensile load in each pneumatic cylinder was manually adjusted to 55 N, which produced an initial tension in the graft of 110 N. The intraarticular graft tension was measured with the knee in full extension using the femoral load cell whose output was corrected for friction in the femoral tunnel. [Color scheme can be viewed in the online issue, which is available at <http://www.interscience.wiley.com>]

The intraarticular graft tension was measured by a load cell (225 N, SM-50, Interface) attached to the femoral fixation device.¹⁰ The intraarticular tension was measured after applying the initial tension (110 N), before extraarticular tension release (with the fixation device inserted), after fixation (i.e., after releasing the extraarticular tension with the tibial fixation device inserted), after insertion of a bone dowel (for WasherLoc tibial fixation only), and after cyclically loading the knee for 300 cycles). The intraarticular tension was measured with the knee in full extension. The intraarticular tension, measured by the femoral fixation transducer, was corrected for tension loss in the femoral tunnel due to friction as described previously.¹⁰

Statistical Analysis

The 134-N anterior limit and 0-N posterior limit of the treated knee were referenced to the intact knee by subtracting the limit of motion of the treated knee from that of the intact knee. A positive value indicates an increase and a negative value indicates a decrease in the limit of motion compared to that of the intact knee. For each tibial fixation device, the effect of the two tensioning methods on the 134 N anterior and the 0 N posterior limits referenced to the intact knee was evaluated with use of an unpaired *t*-test at two time points: after tibial fixation and after cyclically loading the knee 300 times. The level of significance was set at $p < 0.05$. Statistical analyses were performed with commercially available software (SAS, release 8.0, SAS Institute, Cary, NC).

An unpaired *t*-test was performed to compare the effect of the two tensioning methods on the intraarticular graft tension. Separate analyses were performed for each tibial fixation device and each time the intraarticular graft tension was measured: during tensioning, before releasing the extraarticular tension, after inserting the tibial fixation device, after inserting the bone dowel (Washerloc only), and after cyclically loading the knee.

One specimen treated with the simulated method of tensioning by hand was excluded from the statistical

analysis because of an equipment malfunction. Therefore, the results are compiled from 9 specimens treated with the simulated method of tensioning by hand and 10 specimens treated with the tensioning device pinned to the tibia.

RESULTS

The tensioning method did not significantly affect the 134-N anterior limit of motion referenced to the intact knee (Table 1). For the knees treated with the interference screw, the average difference in the 134-N anterior limit referenced to the intact knee between the two tensioning methods was 0.6 mm after tibial fixation ($p = 0.35$) and 0.0 mm after cyclic loading ($p = 0.95$). For the knees treated with the WasherLoc, the average difference between the two tensioning methods was 0.8 mm after tibial fixation ($p = 0.31$) and 0.9 mm after cyclic loading ($p = 0.25$).

The tensioning method did not significantly affect the 0-N posterior limit of motion reference to the intact knee (Table 1). For the knees treated with the interference screw, the average difference in the 0 N posterior limit referenced to the intact knee between the two tensioning methods was 0.0 mm after tibial fixation ($p = 0.78$) and 0.4 mm after cyclic loading ($p = 0.11$). For the knees treated with the WasherLoc, the average difference was 0.4 mm after tibial fixation ($p = 0.36$) and 0.6 mm after cyclic loading ($p = 0.15$).

When comparing tensioning methods using an interference screw (Table 2), no significant difference was found between the intraarticular graft tension during tensioning ($p = 0.30$), before extraarticular tension release ($p = 0.41$), after fixation ($p = 0.73$), and after cyclically loading the

Table 1. Average and Standard Deviation of the 134 N Anterior Limit and the 0 N Posterior Limit Referenced to the Intact Knee (i.e., Difference in the Limit between the Treated Knee and the Intact Knee) Both after Tibial Fixation and after Cyclic Loading for the Interference Screw and WasherLoc

	Interference Screw		WasherLoc	
	134-N Anterior Limit Referenced to the Intact Knee (mm)			
	After Fixation	After Cyclic Loading	After Fixation	After Cyclic Loading
Device pinned to the tibia	-0.1 ± 1.4	1.0 ± 2.0	0.3 ± 1.4	1.4 ± 1.4
Simulated method of tensioning by hand	-0.7 ± 1.4	1.0 ± 2.7	-0.5 ± 1.9	0.5 ± 1.9
	$p = 0.35$	$p = 0.95$	$p = 0.31$	$p = 0.25$
0-N Posterior Limit Referenced to the Intact Knee (mm)				
Device pinned to the tibia	0.1 ± 0.3	0.1 ± 0.3	0.0 ± 0.5	0.0 ± 0.4
Simulated method of tensioning by hand	0.1 ± 0.5	-0.3 ± 0.7	-0.4 ± 1.0	-0.6 ± 1.0
	$p = 0.78$	$p = 0.11$	$p = 0.36$	$p = 0.15$

Table 2. Average and Standard Deviation of the Intraarticular Graft Tension at Different Time Points for the Interference Screw and Washerloc

	Intraarticular Tension with Interference Screw (N)				
	Initial Tension	Before Tension Release	After Fixation	After Inserting Bone Dowel	After Cyclic Loading
Device pinned to the tibia	99 ± 9	151 ± 35	131 ± 30	N/A	89 ± 34
Simulated method of tensioning by hand	95 ± 4	166 ± 39	125 ± 52	N/A	80 ± 61
	$p = 0.30$	$p = 0.41$	$p = 0.73$	N/A	$p = 0.67$
	Intraarticular Tension with WasherLoc (N)				
Device pinned to the tibia	99 ± 6	126 ± 34	112 ± 14	125 ± 30	106 ± 31
Simulated method of tensioning by hand	95 ± 4	125 ± 14	89 ± 17	95 ± 21	67 ± 25
	$p = 0.12$	$p = 0.96$	$p = 0.06$	$p = 0.02^a$	$p = 0.01^a$

^aDenotes statistically significant difference.

knee ($p = 0.67$). Using a WasherLoc (Table 2), no significant difference occurred between tensioning methods when comparing the intraarticular tension during tensioning ($p = 0.12$), before extraarticular tension release ($p = 0.96$), and after fixation ($p = 0.06$); however, the tension was significantly greater for the tensioning device pinned to the tibia both after inserting the bone dowel ($p = 0.02$) and after cyclically loading the knee ($p = 0.008$).

DISCUSSION

We evaluated a tensioning device pinned to the tibia to determine whether the joint reaction loads applied by such a device increase the AP load-displacement of the reconstructed knee compared to tensioning the graft when no joint reaction loads are created and whether the intraarticular graft tension was better maintained. AP load-displacement and intraarticular graft tension were also measured with two tibial fixation methods, the bioresorbable interference screw and WasherLoc, to determine whether any increase in stability depended on the fixation device. Our most important finding was that a tensioning device that created joint reaction loads when pinned to the tibia did not decrease the AP load-displacement and did not overconstrain the knee compared to tensioning with no joint reaction loads. Although the intraarticular graft tension was not affected by the tensioning method for the interference screw, the tension was better maintained for the Washerloc when tensioning with the device pinned to the tibia.

Methods Issues

We did not determine whether tensioning the graft with the knee in flexion rather than full

extension with either tensioning method affected the AP load-displacement. One reason that the knee was tensioned in full extension was because tensioning at 30° flexion decreases range of motion^{7,15} and causes posterior tibial subluxation relative to the femur.^{7,16} Another reason is that the clinical success rate in restoring AP load-displacement and motion is high when the graft is tensioned with the knee in full extension.^{2,3,17} However, manual application of a posteriorly directed force to the proximal anterior surface of the tibia with the knee in 20° and 30° flexion while tensioning the graft manually without a reaction load otherwise increased AP load-displacement in *in vitro* studies.^{18,19} This force posteriorly displaces the tibia, increasing AP load-displacement with the knee in flexion, but overconstrains the knee.²⁰ Further study is required to determine whether this approach improves AP load-displacement without overconstraining the knee and limiting motion.

Because we used a custom-made arthrometer to apply anterior and posterior loads, the effect of the method of tensioning the graft on AP load-displacement was studied at 25° of flexion. Previous studies measuring AP laxity used knee flexion angles in the range 20° to 30°.^{21–24} Although anterior translation is greatest at 30°,^{25,26} the difference in translation between 20° and 30° is small.²⁶ Hence, flexion angles within this range are commonly used to assess AP load-displacement because changes can be easily detected.²⁷

Although nonrandomized, sequential testing was used (i.e., the interference screw was tested before the WasherLoc), this procedure did not cause a carryover effect that affected knee AP load-displacement for the WasherLoc. A carryover effect might have occurred for the WasherLoc if the insertion and removal of the interference screw

fractured the bone. However, the 170-N load applied to the graft to cyclically load the knee is less than the yield load of the interference screw in a foam reinforced tibia (523 ± 126 N).⁸ Further, the condition of the bone was visually inspected after removal of the screw, and the cortex remained intact. Because the bone did not fracture, the testing procedure did not produce carryover effects on AP load-displacement with the two tensioning methods.^{8,10}

Usefulness and Interpretation of Results

Tensioning the graft without any joint reaction loads (i.e., manually) restored the AP displacement to that of a tensioning device that produces joint reaction forces. In clinical practice, a graft can be tensioned without generating joint reaction loads when manually applying either a known or unknown tension to the graft by hand or with a commercially available device. A typical method for applying an unknown tension is through the use of a knob attached to the strands of the graft (e.g., Tie Tensioner, Mitek, Summerville, NJ), whereas a typical method for applying a known tension is to use a spring scale as the tensioning device (e.g., Tension Isometer, MedMetric Corp., San Diego, CA). Conversely, joint reaction loads can be developed either while tensioning a graft when one end of the hamstring graft is left attached to the tibia or when using a commercially available device that attaches to the foot (e.g., Graft Tensioner, Arthrotek Inc.) or tibia. We showed that the AP load-displacement is independent of the tensioning method for the two methods and two fixation devices studied when the initial tension is applied with the knee in extension. Although the intraarticular graft tension was better maintained using the tensioning device pinned to the tibia for the Washerloc both after fixation and after cyclic loading, the increased tension did not improve the 134-N anterior limit of motion.

The joint reaction loads produced by the tensioning device pinned to the tibia did not affect the AP load-displacement of the knee. The most likely explanation is that the force required for tibial device fixation developed corresponding joint reaction loads that equaled or exceeded the loads produced by the tensioning device pinned to the tibia. In that case, the joint reaction loads would have been comparable for both tensioning methods at the time of fixation so that the resulting AP load-displacement was similar for the two methods of fixation.

Also, the observation that the 0-N posterior limit was comparable to that of the intact knee (Table 1)

indicates that the force required for tibial fixation did not overconstrain the knee. The compressive force component developed during tibial fixation might have negated the displacement effect of the posterior force component to some degree. As the compressive force increases, the knee gains stability and becomes more resistant to AP translation from external forces.²⁸⁻³² Our results support this mechanism particularly for the interference screw, because vector analysis shows that the compressive force component dominates the posterior force component by a ratio of 2.5 to 1 when the force required for tibial fixation is directed along the tibial tunnel.

Our study also highlights a difficulty in maintaining AP load-displacement following ACL reconstruction. Immediately after tibial fixation, the AP load-displacement closely matched that of the intact knee for both fixation devices, but AP load-displacement was lost as evidenced by an increase in the 134-N anterior limit referenced to the intact knee after cyclic loading (Table 1). This same phenomenon was observed previously,¹⁰ and is traced to a decrease in the intraarticular graft tension in the unloaded knee after cyclic loading (Table 2); the loss ranged from 31 to 56 N, depending on the type of fixation with a concomitant loss of AP load-displacement. Fixation methods that allow lengthening at the fixation site (e.g., slippage) are prone to lose intraarticular tension, and hence AP load-displacement after cyclic loading.^{10,33}

Because a loss in intraarticular tension from cyclically loading is anticipated, the most effective way to maintain AP load-displacement is to use a high-stiffness graft construct.³³ A high-stiffness construct requires the use of a high-stiffness fixation device on both ends of the graft. A high-stiffness construct is advantageous because it requires substantially less initial tension than a low-stiffness construct to restore AP load-displacement. Therefore, any loss of initial tension, which is inevitable using current fixation methods, will not affect AP load-displacement to the same extent as the loss of initial tension for a low-stiffness construct.³³

In summary, compared to a simulated method of tensioning by hand, tensioning with a device pinned to the tibia did not decrease the 134-N anterior limit and did not cause posterior tibial translation. However, intraarticular graft tension was better maintained with a tensioning device pinned to the tibia for the Washerloc, but not the interference screw. For two commonly used fixation devices, a tensioning device pinned to the

tibia does not improve AP load-displacement at 25° flexion over tensioning by hand when the graft is tensioned at full extension, but does improve the maintenance of intraarticular graft tension for the Washerloc. Consequently, knee AP load-displacement can be restored equally well with the two tensioning methods as long as the same initial tension is applied with the knee in full extension.

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