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Anterior Cruciate Ligament Graft Fixation

Comparison of Hamstring and Patellar Tendon Grafts*

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ABSTRACT

This study assessed the tensile properties of hamstring and patellar tendon anterior cruciate ligament reconstructions in older cadaveric knees (age range, 48 to 79 years). Mechanical testing to failure was conducted by translating the tibia anteriorly at 1 mm/sec with the knee in 20° of flexion. The strongest gracilis-semitendinosus graft fixation technique (103% of intact anterior cruciate ligament) had the tendons doubled and secured with soft tissue washers ($P < 0.01$). However, all reconstructions using gracilis-semitendinosus grafts were significantly less stiff than the intact anterior cruciate ligament specimens regardless of fixation technique ($P < 0.01$). The highest strength patellar tendon graft fixation technique (84% of intact anterior cruciate ligament) was obtained with a combination interference screw and suture technique. The difference in stiffness between a patellar tendon graft and an intact anterior cruciate ligament was not significant when interference screws were placed at both ends of the graft ($P > 0.05$). Both types of grafts failed most often on the tibial side. With appropriate fixation, both grafts approximated the intact anterior cruciate ligament in strength, but only patellar tendon grafts secured with interference screws were comparable in stiffness.

Secure graft fixation is important to the success of ACL reconstruction.[4,6,8] The goal of graft fixation is to prevent stretching or failure at graft fixation sites, and thereby to permit early motion and early weightbearing without the loss of stability.[4,6,8] However, surgeons employ a wide variety of fixation techniques with little consensus on which techniques are best. We believe that this is partly due to a lack of comparative data on the biomechanics of graft fixation.

Previous studies of ACL graft fixation have employed a variety of testing methods using generally older cadavers.[2,9,10,12,15,16] Three studies assessed graft fixation by clamping a graft and applying a direct tensile force to its fixation site.[2,12,15] Robertson et al.[15] performed such "pull-out" tests with grafts attached to cortical bone. They documented that soft tissue washers (238 N maximum load) were superior to suture fixation for hamstring grafts. Matthews et al.[12] similarly tested patellar tendon grafts inserted into bone tunnels and found that 9-mm interference screws were equal to suture fixation in maximum load (460 N). Brown et al.[2] used a similar method with patellar tendon grafts and they reported little difference in maximum load between rear-entry (235 N) or endoscopic (256 N) interference screws.

Two studies of ACL reconstructions in cadaveric knees tested the reconstructions by joint distraction. Kurosaka et al.[10] employed such tests in three young knees and in seven old knees. The strongest fixation they documented was with patellar tendon grafts secured with 9-mm interference screws in young knees (476 N maximum load). Ivey and Li[9] similarly tested ACL reconstructions in old knees and reported low strength for interference screw fixation of patellar tendon grafts, presumably because old specimens were used. They found that soft tissue washers provided the strongest hamstring graft fixation (250 N maximum load).

These prior studies assessed tensile properties using either "pull-out" tests of grafts or distraction tests of ACL reconstructions. The motions used in these tests are not physiologic and the forces that these motions apply to fixation sites may not be clinically relevant.[3,4,6] Since anterior

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tibial translation is the primary motion that applies stress to an ACL in vivo, we believe that it is the best motion to use when testing an ACL reconstruction in vitro.[5,7,11] The tensile properties of the intact ACL depend on the motion used in testing, and we believe that the tensile properties of an ACL reconstruction similarly depend on the motion used in testing.[13,19]

We assessed graft fixation by applying anterior tibial translation to cadaveric hamstring and patellar tendon ACL reconstructions. We tested some common fixation techniques and some previously unreported fixation techniques. Our first objective was to identify graft fixation techniques that yielded ACL reconstructions that were similar to the intact ACL in biomechanical properties. Our second objective was to compare the biomechanical properties of hamstring and patellar tendon ACL reconstructions.

MATERIALS AND METHODS

Nineteen pairs of fresh human cadaveric knees (38 specimens) stored at –20°C were used for testing. Because of bone fracture during testing, the results for one pair of knees from a 94-year-old cadaver were excluded. This left 18 pairs of knees (8 male and 10 female specimens) with an average age of 69.5 years (range, 48 to 79).

Specimen preparation

Dissection and specimen preparation were performed after thawing each knee for 24 hours at room temperature. Knees were excluded if by inspection they had severe degenerative arthritis, prior knee surgery, or prior major trauma. A 10-mm wide patellar tendon graft was harvested with bone plugs 25 mm in length at each end. The plugs were contoured to just pass through a 10-mm diameter sheath (part no. 013526, Acufex Microsurgical, Inc., Mansfield, MA). The gracilis and semitendinosus tendons were harvested by dissecting them from their respective muscles and leaving them either attached to the tibia or taking them as free grafts, depending on the fixation technique. The ACL was left intact in 14 knees for preliminary testing to establish intact ACL tensile properties. All other soft tissues and the fibula were dissected from the femur and tibia, leaving bone shafts a minimum of 18 cm in length. Normal saline was used to keep the specimens moist during the dissection and testing.

Fixation techniques

In each knee, an ACL reconstruction was first performed and tested using a gracilis and semitendinosus graft. This graft was then removed and an ACL reconstruction was performed and tested using a patellar tendon graft. Femoral and tibial drill holes were sized for the gracilis and semitendinosus grafts and were between 7 and 9 mm to allow easy passage of the grafts. For the ACL reconstructions using the patellar tendon grafts, the holes were rereamed to 10 mm. The femoral and tibial holes were drilled outside-in to the anatomic insertions of the ACL using a commercial drill guide system (Acufex Microsurgical, Inc.). Grafts were tensioned with the knee in extension and with the posterior femoral condyles and the posterior tibial plateau in the same coronal plane. We found by measurement that this technique produced intraarticular graft lengths to within 5 mm of the intact ACL resting length.

Four fixation techniques were evaluated using gracilis and semitendinosus grafts (Fig.1).

GSTsut. The gracilis and semitendinosus tendons were taken as free grafts. One suture, no. 2 Ethibond (Ethicon, Inc., Somerville, NJ), was placed in a whipstitch fashion (six throws) in the end of each tendon. The four suture strands at each end of the composite graft were tied to either a femoral or tibial post (25 × 6.5 mm screw and metal washer, Synthes Ltd., Paoli, PA).

DGSTsut. The gracilis and semitendinosus tendons were

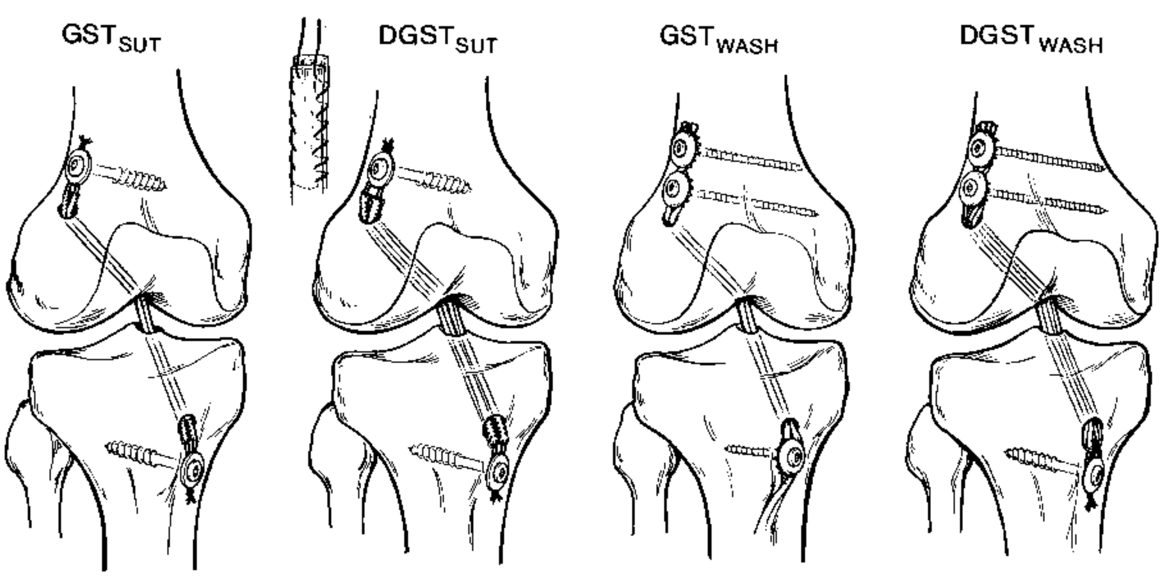

Figure 1. The hamstring fixation techniques (see "Material and Methods" under "Fixation Techniques" for the description of each technique).

taken as free grafts and bisected or doubled to produce four tendon limbs. One suture, no. 5 Ethibond (Ethicon, Inc.), was placed in whipstitch fashion (six throws) in the two gracilis limbs and another similar suture was placed in the two semitendinosus limbs. The four suture strands at each end of the composite graft were tied to either a femoral or tibial post (25 × 6.5 mm screw and metal washer, Synthes Ltd.).

GSTwash. Single-limb gracilis and semitendinosus grafts were secured to the femur by weaving them in opposite directions around two soft tissue washers (6.0 mm, Synthes Ltd.) and bicortical screws (4.5 mm, Synthes Ltd.). The tendons were secured to the tibia by their biologic insertions and by one soft tissue washer (6.0 mm, Synthes Ltd.) and bicortical screw (4.5 mm, Synthes Ltd.).

DGSTwash. The gracilis and semitendinosus tendons were taken as free grafts and folded to produce two looped ends and four free ends. The free ends were secured to the femur by two soft tissue washers and bicortical screws as in the GSTwash technique. The looped ends were secured to the tibia by three sutures (no. 5 Ethibond) placed through the looped ends and tied to a post (25 × 6.5 mm screw and metal washer, Synthes Ltd.).

Four fixation techniques were evaluated for patellar tendon grafts (Fig. 2).

PTint. Femoral and tibial fixation was done with interference screws (9 × 25 mm, Acufex Microsurgical Inc.) placed in an "outside-in" position.

PTsut. Femoral and tibial fixation was done with three sutures (no. 5 Ethibond) placed through 2.0-mm diameter holes in each bone plug and tied to femoral and tibial posts (25 × 6.5 mm screws and metal washers, Synthes Ltd.).

PTendo. Femoral fixation was done with "endoscopic" interference screws (7.0 × 25 mm., Acufex Microsurgical Inc.) placed in an inside-out position and tibial fixation with done with sutures, as in PTsut.

PTis-sut. This procedure combined interference screw (PTint) and suture fixation (PTsut) on the femur and tibia.

Biomechanical testing

Biomechanical tests were performed on the ACL reconstructions using an Instron 1331 materials testing machine (Instron Corp., Canton, MA). The femur and tibia were mounted using custom fixtures that held the knee in 20° of flexion. An approximately 2-mm separation of the articular surfaces was maintained to eliminate femoral-tibial shear forces. An 8-mm bolt was placed through each fixture and bone shaft to prevent axial rotation. Tests were conducted by translating the tibia anteriorly with all other motion constrained.

A preconditioning protocol was followed to eliminate crimping of the ACL grafts before testing. A preload of 50 N was applied, then the tibia was translated anteriorly 0.6 mm (approximately 2% strain) 10 times at 1 Hz, a 50-N load was then maintained until failure testing. The amount of translation that occurred during this conditioning process was not recorded, but visually it appeared to be no more than several millimeters. A tensile test was conducted by translating the tibia anteriorly 50 mm at 1 mm/sec. The mechanism of failure was recorded. Tensile properties were measured as previously described.[17] Yield load was taken as the point on the load-displacement curve where the slope first clearly decreased. Maximum load was the peak load sustained by the graft. Displacements at the yield and maximum load points were recorded. Stiffness was the slope of the curve in its linear region determined by fitting a tangential line to the load-displacement curve.[17] Stiffness is a parameter that best correlates with the clinical grading of joint "laxity" on physical examination. In a physical examination an examiner applies force to a knee and estimates the displacement that occurs. The greater the stiffness, the less the displacement for a given force and the lower the laxity grade.

To obtain baseline data on intact ACL strength, the femur-ACL-tibia complex was tested in 14 knees. In each

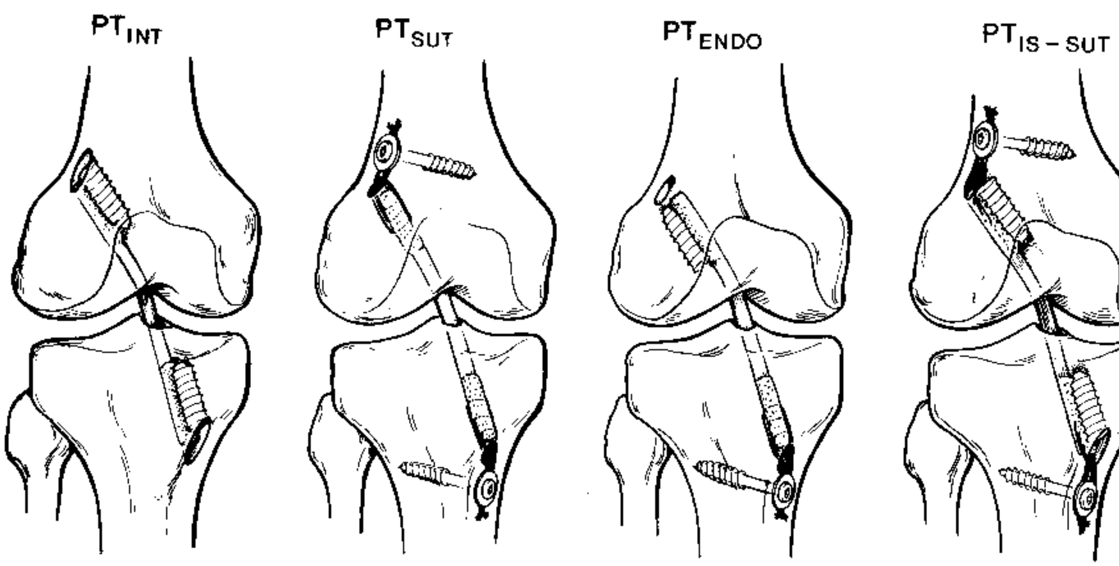

Figure 2. The patellar tendon fixation techniques (see "Materials and Methods" under "Fixation Techniques" for the description of each technique).

TABLE 1
Side-to-side fixation techniques in each testing group[a]

Group	ACL	GST[b]	PT[c]
1 (7 pairs of knees)	Tested	GSTwash OTT/GSTwash TTC	PTint/PTsut
2 (5 pairs of knees)	Not tested	GSTwash/GSTsut[d]	PTint/PTendo
3 (6 pairs of knees)	Not tested	DGSTwash/DGSTsut	PTis-sut/PTendo

[a] The fixation techniques are described in "Materials and Methods" under "Fixation Techniques," and they are depicted in Figures 1 and 2.
[b] GST, gracilis and semitendinosus; OTT, graft placed over the top of the femoral condyle; TTC, graft placed through the femoral condyle.
[c] Patellon tendon.
[d] Because of errors in dissection and specimen preparation, two GSTwash specimens were converted to GSTsut specimens.

of these 14 knees, ACL reconstructions were performed and tested immediately after the intact ACL test.

While the variety of fixation methods evaluated prevented side-to-side statistical comparisons, a protocol was followed whereby different fixation techniques were randomized between the right and left knees from the same cadaver (Table 1). This was done to reduce the confounding effects of cadaveric variability. Using this protocol, the 18 pairs of cadaveric knees were divided into three groups. Within each group, two gracilis and semitendinosus fixation techniques and two patellar tendon fixation techniques were tested (Table 1). The GSTwash, PTint, and PTendo fixation techniques were tested in two groups; therefore, a greater number of observations were obtained using these three techniques.

For comparative purposes, 5 GSTwash grafts were routed over the top of the femoral condyle and 10 GSTwash grafts were placed through the femoral condyle. The tensile properties for these two graft placements did not differ significantly ($P > 0.45$); therefore, the results for these two graft placements were pooled.

Data for six knees were not available because of failures in dissection (two knees), failures in data acquisition (two knees), and severe tibial plateau fractures (two knees). The mean ages of the cadaveric knees used for each fixation technique varied slightly (range, 64 to 71 years), but not significantly ($P > 0.18$).

Statistical analysis

Statistical analysis was performed using the SAS statistical package (SAS Institute, Cary, NC). A two-way analysis of variation (ANOVA) was performed with fixation technique and cadaver as the model variables. Dunnett's procedure was used to adjust for multiple comparisons when contrasting each fixation technique to the intact ACL. Secondary comparisons between specific fixation techniques were performed using two-sample and paired t-tests.

RESULTS

Maximum load

The average maximum load (±SD) of the intact ACL was 800 ± 469 N (Table 2). The global ANOVA for maximum load comparing all fixation techniques and the intact ACL was highly significant ($P = 0.003$). Within the gracilis and semitendinosus fixation group there was only one technique that exceeded the intact ACL in strength, DGSTwash (821 ± 219 N). The DGSTwash and DGSTsut (573 ± 109 N) techniques were not significantly different in strength from the intact ACL ($P > 0.05$). In a direct comparison (t-test), the DGSTwash technique was significantly stronger than the DGSTsut technique ($P < 0.01$). Within the patellar tendon fixation group, no technique exceeded the intact ACL in strength. However, two techniques, PTendo (588 ± 282 N) and PTis-sut (674 ± 206 N), were not significantly different in strength from the intact ACL ($P > 0.05$) (Table 2).

TABLE 2
Tensile properties of the intact ACL and the graft fixation techniques (mean value with SD in parentheses)[a]

Structure	Maximum Load (N)	Stiffness (N/mm)	Displacement[b] (mm)
ACL (N = 14)	800 (469)	66 (26)	12 (5)
GSTsut (N = 7)	335 (87)[c]	16 (16)[c]	26 (12)[c]
DGSTsut (N = 6)	573 (109)	18 (5)[c]	22 (8)
GSTwash (N = 15)	519 (165)[c]	20 (5)[c]	20 (10)[d]
DGSTwash (N = 5)	821 (219)	29 (7)[c]	26 (12)[c]
PTint (N = 10)	423 (175)[d]	46 (24)	10 (5)
PTsut (N = 7)	396 (124)[c]	27 (13)[c]	13 (9)
PTendo (N = 11)	588 (282)	33 (14)[c]	17 (10)
PTis-sut (N = 5)	674 (206)	50 (21)	8 (14)

[a] The fixation techniques are described in "Materials and Methods" under "Fixation Techniques," and they are depicted in Figures 1 and 2.
[b] Displacement to point of initial failure when graft load first decreased.
[c] Significantly different from intact ACL ($P < 0.01$).
[d] Significantly different from intact ACL ($P < 0.05$).

Stiffness

The average stiffness (±SD) for the intact ACL was 66 ± 26 N/mm, and there were no gracilis and semitendinosus or patellar tendon graft fixation techniques with higher values (Table 2). The global ANOVA for stiffness, comparing all fixation techniques including the intact ACL, was highly significant ($P = 0.0001$). The stiffest hamstring graft, DGSTwash (29 ± 7 N/mm) had less than half the stiffness of the intact ACL, and all of the gracilis and semitendinosus fixation techniques were significantly less stiff than the intact ACL ($P < 0.01$). The doubled gracilis and semitendinosus grafts secured with washers were significantly stiffer than the doubled gracilis and semitendinosus grafts secured with sutures ($P < 0.001$, group t-test). The

PTint (46 ± 24 N/mm) and PTis-sut (50 ± 21) N/mm fixation techniques had stiffness values close to that of the intact ACL. These stiffness values were not significantly different from the stiffness value of the intact ACL ($P >$ 0.05). Both of these techniques placed interference screws at both ends of the graft.

Displacement at yield load

The intact ACL began to fail (displacement at yield load) at an average displacement (±SD) of 12 ± 5 mm. The global ANOVA for displacement at yield load comparing all fixation techniques including the intact ACL was highly significant ($P = 0.001$). All of the gracilis and semitendinosus grafts began to fail at higher average displacements, 20 mm or greater, than the intact ACL. This difference was significant ($P < 0.05$) for all of the techniques except DGSTsut ($P < 0.07$). The patellar tendon grafts failed on average at shorter displacements than the gracilis and semitendinosus grafts. Two patellar tendon fixation techniques, PTint (10 ± 2 mm) and PTis-sut (8 ± 2 mm), failed at shorter average displacements than the intact ACL. None of the failure displacements for the patellar tendon grafts were significantly different than the initial failure displacement for the intact ACL ($P > 0.05$).

Mechanism of failure

There were some characteristic mechanisms of failure for each gracilis and semitendinosus and patellar tendon fixation technique (Table 3). The GSTwash grafts failed by tearing at their tibial biologic insertions, combined with slippage beneath the tibial washer. The GSTsut grafts failed by either suture rupture or graft-suture disruption. The DGSTwash and DGSTsut grafts failed by a generalized stretching of the entire graft, sometimes accompanied by tibial post pull-out or suture rupture. Patellar tendon grafts secured by sutures (PTsut, PTendo, and PTis-sut) often failed by fracture of the bone plugs at a suture hole. The PTint grafts failed in all cases by bone plug slippage past interference screws, usually on the tibial side. The PTendo and PTis-sut techniques failed by a combination of mechanisms.

TABLE 3
Mode of failure and incidence for ACL reconstructions

Structure	Mode of failure	Incidence
GSTsut	Suture rupture and suture-tendon disruption	4
	Suture-tendon disruption	2
	Suture rupture	1
DGSTsut	Suture-tendon stretch, no disruption	5
	Tibial post pullout	1
GSTwash	Pullout beneath tibial washer	15
DGSTwash	Tendon stretch, no disruption	2
	Tibial post pullout	2
	Suture rupture	1
PTint	Pullout around tibial screw	8
	Pullout around femoral screw	2
PTsut	Bone-tendon rupture	3
	Bone plug fracture	3
	Tibial post pullout	1
PTendo	Bone plug fracture	6
	Pullout around femoral screw	3
	Bone-tendon rupture	2
PTis-sut	Bone plug fracture	4
	Pullout around tibial screw and suture rupture	1

Age and tensile parameters

For the intact ACL and for each graft fixation technique, correlation coefficients were calculated between age and, in turn, maximum load, stiffness, and displacement at yield load. The only significant correlations with age were stiffness ($R^2 = 0.682$, $P < 0.01$) and maximum load ($R^2 = 0.454$, $P = 0.013$) for the intact ACL group. No significant or consistent trends were otherwise noted between age and graft tensile properties.

DISCUSSION

In this cadaveric study, hamstring and patellar tendon ACL reconstructions were performed with graft placements and graft attachments similar to those used clinically. The ACL reconstructed knees were tested to failure by translating the tibia anteriorly. This testing method applied forces to the reconstructed ACL using the primary knee motion that applies stress to the ACL.[5,7,11] This is important because of graft bending at drill hole entrance and exit sites.[3] When a graft is pulled at an angle to a drill hole, some shear forces are generated between the graft and the edge of the drill hole.[3] These shear forces will stress shield the graft fixation site. Such stress shielding is likely to be minimal in pull-out tests when grafts are pulled in line with bone tunnels; such stress shielding will not be physiologic in knee distraction tests. It has been demonstrated that the intact ACL has mechanical properties that are affected by the motion used in testing,[13,19] and we believe that this same relationship exists with an ACL reconstruction. Therefore, anterior tibial translation was chosen as the testing motion in this study.

The strongest gracilis and semitendinosus fixation identified in this study occurred when the tendons were doubled, the free ends wrapped around two femoral soft tissue washers, and the closed ends looped around a tibial post. The tensile strength of this fixation was considerably greater than has been previously reported (250 N maximum load) with hamstring grafts.[9] The strength of this fixation was comparable with that of our control ACL specimens, but the stiffness (29 N/mm) was less than half that of the controls.

We noted that gracilis and semitendinosus grafts left with the natural attachments to the tibia (GSTwash) were relatively weak because of failure by slow tearing from their tibial insertions, despite the reinforcement of a washer. Ivey and Li[9] also documented that the biologic insertions of hamstring tendons were relatively weak (250 N maximum load) when the tendons were pulled at a right angle to their normal alignment.

All hamstring grafts with suture fixation failed with prolonged pullouts, culminating in either complete suture-graft disruption (GSTsut) or marked graft stretching without disruption (DGSTsut). The washer technique was superior to the suture technique in achieving hamstring ACL reconstructions with closer-to-normal strength and stiffness. Robertson et al.[15] similarly reported greater strength with washers (179 N maximum load) as compared with sutures (71 N maximum load) in the fixation of tendinous tissues.

In contrast to the hamstring ACL reconstructions, the ACL reconstructions using patellar tendon grafts were notable for their close-to-normal ACL stiffness (Fig. 3). The use of interference screws at both ends of the graft resulted in maximum stiffness (46 mm to 50 N/mm). Coincident with this increased stiffness were small displacements to failure (8 to 10 mm). Patellar tendon grafts failed generally on the tibial side by bone block slippage past interference screws or by bone block fracture through suture holes. Bone block fractures were not seen when interference screws were used alone, perhaps because interference screws distribute stress evenly along the bone plugs.[16] Suture fixation of patellar tendon grafts produced longer composite grafts (suture-bone-tendon-bone-suture), which was reflected in a trend toward lower stiffness (27 N/mm).[6,9]

The knees with patellar tendon grafts that had the highest absolute values for maximum load (674 N) and stiffness (50 N/mm) had interference screws and sutures placed at both ends of the grafts. The strength and stiffness of these ACL reconstructions were not significantly different than that of the intact ACL. In three young cadaveric knees, Kurosaka et al.[10] reported the highest previous fixation strength (476 ± 192 N) and stiffness (58 ± 8 N/mm) of patellar tendon grafts using interference screws alone. For comparison, our ACL reconstructions on older cadaveric knees using patellar tendon grafts secured with interference screws alone had a strength of 423 ± 125 N and a stiffness of 46 ± 24 N/mm.

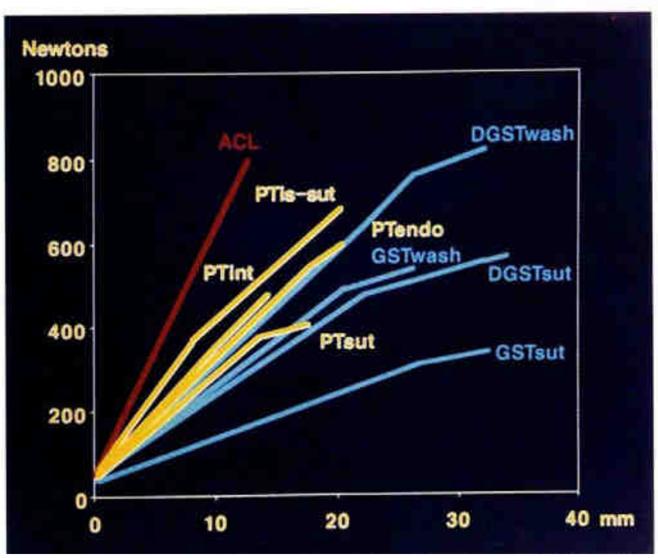

Figure 3. Load-displacement curves for the intact ACL and each graft-fixation technique combination. The points of 50 N preload, yield load, and maximum load were connected to produce the curves for each technique. (PT grafts in yellow, GST grafts in turquoise).

Patellar tendon grafts secured with femoral inside-out interference screws and tibial sutures (PTendo) were not significantly different in strength from the intact ACL, but their stiffness (33 N/mm) was below that for the intact ACL. There were two technical differences between our PTendo fixation technique and the clinical endoscopic fixation technique.[14] First, the drill holes in this study were produced by drilling outside-in, using a conventional drill guide, while clinical endoscopic drill holes are drilled inside-out, using an endoscopic drill guide.[14] The orientation of these two types of drill holes is different, with the conventional drill hole having a more acute angle to the shaft of the femur.[3,14] We speculate that the sharper bend of a graft into a conventional drill hole creates greater shear forces that stress shield the femoral fixation site.[3] Second, inside-out screws were inserted directly in line with the holes in this study and not at an angle to the hole, as can occur clinically.[1] These two factors—hole alignment and ease of screw placement—would suggest that our in vitro techniques provide upper bounds on the strength and stiffness of the endoscopic technique.

Reported strength values for the intact ACL in older cadavers have ranged from 415 to 734 N.[4,9,10,13,19] These prior studies employed joint distraction either in line with the femur, tibia, or ACL. Our slightly higher value of 800 N suggests that the ACL resists anterior tibial translation better than femoral-tibial distraction. Conversely, our stiffness value of 66 N/mm for the intact ACL is lower than has previously been reported using joint distraction in older cadavers (74 to 129 N/mm).[9,10,13,19] This difference in stiffness may be due to bending of the femur and tibia during our tests. Such bending was observed, but attempts to measure it with calipers were unsuccessful.

For reference, average strength measurements for young ACL specimens have been reported to be as high as 2160 N and stiffness measurements as high as 242 N/mm.[19] Also, it has been suggested that loads up to 445 N are applied to the ACL during activities of daily living.[7,11,13]

We tested patellar tendon grafts after we tested gracilis and semitendinosus grafts on the same knees; it is possible that this may have biased the patellar tendon results. Cancellous bone along the femoral and tibial canals may have been weakened by hamstring graft testing, which could particularly affect the results of interference screw fixation. However, the protocol did necessitate enlarging the bone tunnels before patellar tendon graft fixation and we believe this eliminated areas of bone injury created by gracilis and semitendinosus testing. When screws were placed in cortical bone for patellar tendon fixation, the screws were placed away from any prior drill holes used for gracilis and semitendinosus fixation. In two knees, hamstring grafts failed by cortical fractures about the tibial holes. The results for these two specimens were not reported, and patellar tendon grafts were not tested in these two knees.

Our study had three important limitations. The first was donor age. The mechanical properties of connective tissues deteriorate with age, and the knees used in this study were from older donors.[4,19] If we had tested specimens from the 2nd and 3rd decades of life (the age range within which most ACL reconstructions are performed), then it is probable that greater strength and stiffness measurements would have been made. Our conclusions could be affected if some fixation techniques were relatively more dependent on cadaveric age. We speculate that our use of older cadavers may have biased the results against interference screw fixation because that technique depends particularly on bone quality.[9,10] Yet, within the age range we tested (48 to 79 years), we did not find a correlation between cadaveric age and graft fixation tensile properties. The only age-related parameters we did document were strength and stiffness in the control ACL specimens.

The second potential limitation was the static nature of the tensile tests. We tested ACL reconstructions using a static displacement test to failure, but in the clinical setting, forces well below the threshold for failure are applied dynamically to ACL reconstructions.[7,11] It is possible that some fixation techniques that appear strong statically may prove clinically weak under conditions of dynamic loading. Dynamic loading of cadaveric ACL reconstructions has been reported,[3] but the technique has limitations because of graft abrasion at bone tunnels and because, if loading is done over hours, soft tissue deterioration will occur.[3,18]

The third limitation was the potential variability in healing between different grafts and the impact of fixation on this healing.[4] We only studied the biomechanical properties of ACL reconstructions as they would appear immediately after surgery. It is possible that some graft-fixation combinations, while being statically strong, might fail clinically because of slow or poor graft healing. We believe that in vitro tests provide only a first-order evaluation of graft fixation and that animal and clinical studies are required to fully validate a fixation technique.[4,17]

Based on our in vitro testing of ACL reconstructions, we suggest that hamstring grafts be doubled and fixed to the femur with washers, and fixed to the tibia by looping the grafts around a post. We suggest that patellar tendon grafts be fixed with interference screws backed up by sutures, particularly on the tibial side. We note that ACL reconstructions using patellar tendon grafts and interference screws have a closer-to-normal ACL stiffness than do hamstring grafts. Clinical studies will be necessary to determine the impact of this difference in stiffness on surgical outcome.

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DISCUSSION

Robert J. Johnson, MD, *Burlington, Vermont:* This article demonstrated that fixation of a doubled gracilis and semitendinosus tendon graft using a double screw and washer technique can provide fixation strength greater than the intact, but aged, ACL specimens used in this study. Interference fit screws were unable to match this fixation strength, but were only slightly reduced from and not statistically different from that of their intact ACL specimens. Thus, the two fixation methods appear to be equally efficacious. The authors demonstrated that fixation with sutures was inferior for either of the grafts that they used. It must be recalled, as the authors emphasized, that the fixation strengths that they obtained in their specimens were approximately one-third the strength of a normal, young ACL specimen.

Another important factor that the authors observed was that the stiffness of the hamstring tendons, no matter how well they were fixed, was, at best, approximately half that of a normal ACL. This must be carefully considered by surgeons using hamstring grafts, for the ultimate stiffness of the ACL reconstruction may be as important as the final strength in regard to the outcome of the procedure.

The only criticism I have of this study is that even though the authors found no statistically significant difference between patellar tendon grafts fixed with interference screws alone and those augmented with sutures, they advised the latter procedure. I wonder if the added surgical time and the potential need for removing a permanent fixation screw later are really worthwhile. I urge the authors to continue their work and to provide us with information on how their fixation techniques stand up to cyclic loading during post-operative rehabilitation, as Graf and his colleagues have demonstrated.

Authors' Reply: We appreciate Dr. Johnson's thoughtful comments. In regard to augmenting interference screw fixation with sutures, we believe that this is a judgment that the surgeon should make at the time of surgery. If an interference screw appears to be well directed and well engaged, then it has been our clinical experience that interference screw fixation alone will be adequate. If, however, the quality of the bone is poor, or the insertion torque is low, or for whatever reason the fixation is suspect, then we do not hesitate to "back up" our interference screw fixation with sutures tied around a post. When we compared interference screw plus suture fixation directly to interference screw fixation alone, the combined technique was significantly stronger (two-sample t-test, $P = 0.01$).