Biomechanical Evaluation of Posterior Cruciate Ligament Reconstruction With Quadriceps Versus Achilles Tendon Bone Block Allograft

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Background: Long-term studies of posterior cruciate ligament (PCL) reconstruction suggest that normal stability is not restored in the majority of patients. The Achilles tendon allograft is frequently utilized, although recently, the quadriceps tendon has been introduced as an alternative option due to its size and high patellar bone density.

Purpose/Hypothesis: The purpose of this study was to compare the biomechanical strength of PCL reconstructions using a quadriceps versus an Achilles allograft. The hypothesis was that quadriceps bone block allograft has comparable mechanical properties to those of Achilles bone block allograft.

Study Design: Controlled laboratory study.

Methods: Twenty-nine fresh-frozen cadaveric knees were assigned to 1 of 3 groups: (1) intact PCL, (2) PCL reconstruction with Achilles tendon allograft, or (3) PCL reconstruction with quadriceps tendon allograft. After reconstruction, all supporting capsular and ligamentous tissues were removed. Posterior tibial translation was measured at neutral and 20° external rotation. Each specimen underwent a preload, 2 cyclic loading protocols of 500 cycles, then load to failure.

Results: Construct creep deformation was significantly lower in the intact group compared with both Achilles and quadriceps allograft ($P = .008$). The intact specimens reached the greatest ultimate load compared with both reconstructions (1974 ± 752 N, $P = .0001$). The difference in ultimate load for quadriceps versus Achilles allograft was significant ($P = .048$), with the quadriceps group having greater maximum force during failure testing. No significant differences were noted between quadriceps versus Achilles allograft for differences in crosshead excursion during cyclic testing (peak-valley [P-V] extension stretch), creep deformation, or stiffness. Construct stiffness measured during the failure test was greatest in the intact group (117 ± 9 N/mm, $P = .0001$) compared with the Achilles (43 ± 11 N/mm) and quadriceps (43 ± 7 N/mm) groups.

Conclusion: While the quadriceps trended to be a stronger construct with a greater maximum load and stiffness required during load to failure, only maximum force in comparison with the Achilles reached statistical significance. Quadriceps and Achilles tendon allografts had similar other biomechanical characteristics when used for a PCL reconstruction, but both were inferior to the native PCL.

Clinical Relevance: The quadriceps tendon is a viable graft option in PCL reconstruction as it exhibits a greater maximum force and is otherwise comparable to the Achilles allograft. These findings expand allograft availability in PCL reconstruction.

Keywords: posterior cruciate ligament; PCL; quadriceps; Achilles; biomechanics

Injuries to the posterior cruciate ligament (PCL) are infrequent and comprise approximately 3% of all knee injuries.[15] Typically, a PCL injury occurs with a traumatic event that results in a significant posterior translation of the tibia on the femur, such as a fall on a flexed knee with the foot in plantar flexion or during a dashboard-type injury in a motor vehicle accident. PCL injuries may also occur as a component of a multiligamentous knee injury or knee dislocation. Isolated PCL injuries, and even those associated with multiligamentous knee injuries,[31] can often be managed nonoperatively with satisfactory results.[30] While the vast majority of patients do well with conservative treatment, some continue to be symptomatic, whether from

instability, or more commonly, from anterior knee pain.[4,30] Long-term studies have suggested that these individuals may progress to medial and patellofemoral compartment arthritis.[4] In these clinical scenarios, a PCL reconstruction may be recommended.

The outcome of PCL reconstructions have been quite variable and have not had the same success in restoring knee stability as anterior cruciate ligament (ACL) reconstructions.[3,5,21,23] Numerous surgical techniques have been described, including open transtibial, open tibial inlay, arthroscopic transtibial, and arthroscopic tibial inlay techniques.[10] Both single- and double-bundle techniques have also been described. Currently, the most frequently employed technique is a transtibial technique with an Achilles tendon allograft.[21]

Recently, the quadriceps tendon has become an increasingly popular option for ACL reconstructions due to its large size and stiffness.[14] The use of a quadriceps tendon allograft as an option for PCL reconstruction has not been extensively studied, though several reports describe the use of a quadriceps tendon autograft with good results.[5,6,34] The potential of using a quadriceps tendon allograft is intriguing as its large size and stiffness may hopefully allow surgeons to more accurately restore the anatomic footprint and stiffness of the native PCL. There is a paucity of data surrounding the initial fixation strength and biomechanical function of either the quadriceps or Achilles tendon bone block to overall construct stability in PCL reconstructions.

The purpose of this study was to biomechanically evaluate the initial fixation strength of PCL reconstruction techniques using quadriceps and Achilles tendon bone block allografts in a human cadaveric model. An additional objective was to compare the time zero reconstruction properties to those of the intact PCL. This study was designed to test the hypothesis that a quadriceps bone block allograft has comparable biomechanical construct properties to that of the Achilles bone block allograft and therefore can be considered as an alternative allograft option for PCL reconstruction.

METHODS

Specimen Preparation

Twenty-nine fresh-frozen cadaveric knee specimens (age range, 47-69 years) were randomized to 3 groups: (1) intact PCL (n = 7), (2) PCL reconstruction with Achilles tendon bone block allograft (n = 11), or (3) PCL reconstruction with quadriceps tendon bone block allograft (n = 11). Each knee specimen underwent a computed tomography (CT) scan where 0.6-mm slices were obtained for all orientations (axial, coronal, and sagittal). The file was reformatted into 1-mm slices for analysis. Bone mineral density (BMD) was calculated in the axial plane, using Mimics software for the femur, medial condyle, and tibia at the anatomical location of the PCL reconstruction tunnels. Prior to reconstruction, all specimens were thawed for 24 hours and stripped of skin and muscle to expose the joint capsule. The specimens were kept moist with saline-soaked towels throughout preparation. The collateral ligaments, anterior cruciate ligament, meniscus, and transverse intermeniscal ligaments were left intact.

Achilles and quadriceps bone block allografts (age range, 38-75 years) were processed by Allosource using AlloTrue technology along with low-dose gamma irradiation (1.5 Mrad) following FDA 21 CFR 1271 and AATB standards. Allografts underwent CT scanning using the same conditions previously mentioned, and full-thickness BMD of the bone blocks was calculated in the axial plane for the central portion of the bone block nearest the tendon. Prior to use for PCL reconstruction, the width and thickness of each allograft was measured using Hexagon Metrology digital calipers, accurate to 0.01 mm, in 5 locations along the length to calculate an average cross-sectional area (CSA) for each graft. This procedure was repeated once the allografts were prepared for PCL reconstruction, using the central, full-thickness portion of each graft. The grafts were prepared in a standard fashion with an 11-mm-wide by 25-mm-long bone plug that was contoured to fit easily through an 11-mm sizing tube. The tendon was cut to an overall length of approximately 100 mm prior to tensioning. A single No. 5 Ethibond suture (Ethicon Inc) was placed through each bone plug and a second No. 5 Ethibond suture was whipstitched through the distal tendon in standard fashion. Immediately prior to reconstruction, each sized allograft was pretensioned to 15 lbs with a tensioning board for 15 minutes. Allografts were randomly assigned to a corresponding knee specimen group.

Surgical Technique

A transtibial reconstruction technique with a calcaneal or patellar bone block was employed for both the Achilles and quadriceps tendon allograft specimens. Prior to the reconstruction, the knees were fully vented and a 2-mm Kirschner wire was placed into the tibial plateau in an antegrade fashion flush with the distal end of the lateral

femoral condyle with the knee in 90° of flexion. This was later used to ensure that the anatomical relationship of the tibia on the femur was restored with the reconstruction procedure at the time of mechanical testing. Anatomical topographical landmarks were then utilized to guide both the femoral and tibial tunnel positions.[13] A tibial guide and beath pin was then placed into the centerpoint of the anatomic tibial footprint of the PCL, between the anterolateral (AL) and posteromedial (PM) bundles, and an 11-mm tunnel was drilled with a fully fluted reamer. The femoral tunnel was then drilled, at the centerpoint between the AL and PM bundles, to 11 mm in an inside-out fashion using an acorn reamer. A No. 5 Ethibond passing suture was then placed through the femoral and tibial tunnels to pass the graft in a retrograde fashion through the tibial tunnel and into the femoral tunnel. The bone plug was advanced until it was flush with the aperture of the femoral tunnel. The suture from the femoral plug was then tied over a bicortical screw post and washer. The soft tissue portion of the graft was then advanced through the tibial tunnel. The graft was then maximally manually tensioned with the knee in 90° of flexion with a compressive axial load, and the suture tied to the end of the graft was fixed over a bicortical screw post and washer. Additional aperture fixation was then provided with polyether-ether-ketone (PEEK) screws (Arthrex) in both the femoral (8 mm × 28 mm) and tibial (7 mm × 23 mm) tunnels.

Testing Protocol

The tibia and femur of each specimen were potted in polyvinyl chloride (PVC) with dental acrylic (Isocryl; Lang Dental). Specimens were placed in custom fixtures and secured at 90° of flexion to test posterior tibial translation in a mechanical testing system (Insight 5; MTS Corp) with a 5000-N load cell. Specimens were oriented using the 2-mm Kirschner wire placed in the tibial plateau of intact knees, described above, as a guide. Once oriented, the position on the MTS stage and crosshead height was marked. Then, all supporting capsular tissues were removed including the collateral ligaments, menisci, and ACL to isolate the native PCL or allograft.

All testing was performed at room temperature, where specimens were kept hydrated by spraying with saline during testing and wrapped in saline-soaked gauze during rest periods. A preload of 20 N for 2 minutes was applied to each specimen prior to testing. The peak cyclic load of 100 N was chosen to span 1% to 5% of the maximum load achieved during pilot tests of intact PCL specimens, which was well within the linear region of the pull-to-failure test. Each specimen underwent 3 cyclic loading regimens of 500 cycles each (neutral rotation, 20° external rotation, and repeated neutral position). The neutral cyclic regimen was repeated to determine the effect of rotation and repeated testing on construct properties. After each of the cyclic regimens, the specimen was returned to the original marked position and allowed to rest for 15 minutes. Finally, the specimen was loaded until failure, at neutral rotation, at a rate of 1 mm/s.

Data and Statistical Analysis

Load-displacement curves were analyzed for both cyclic and failure testing. For cyclic testing, extension (P-V) was measured as the amount of excursion between the peak and valley of the last cycle of the first neutral position test in an attempt to show the property of tissue stretch. Stretch was also calculated as the amount of excursion between the peak and valley of the last cycle of the 20° external rotation position test. Creep deformation was computed as the peak displacement of the last cycle (500) relative to that of the first cycle. For failure testing, the maximum load (peak load) and stiffness, defined as the slope of the linear region, were calculated.

A 1-way analysis of variance (ANOVA) was used to compare properties between the 3 groups. A Tukey post hoc test was then used to determine differences between the 3 groups with an honest significant difference. For comparisons where only the 2 PCL reconstruction groups were considered, a Student t test (unpaired) was used. All statistical analysis was conducted in GraphPad Prism, with significance set at $P < .05$. Measured values were tested for Gaussian distribution with a normal distribution probability greater than 95%.

RESULTS

Knee specimen demographics were not significantly different between the 3 groups for age ($P = .79$), body mass index (BMI) ($P = .16$), and BMD (femur, $P = .77$; medial condyle, $P = .98$; tibia, $P = .80$), as seen in Table 1.

For Achilles and quadriceps allograft specimens, no differences were observed between the 2 groups for age ($P = .61$) and BMI ($P = .86$), as seen in Table 2.

However, the BMDs for the bone block were significantly different between the Achilles and quadriceps allografts ($P = .0032$), demonstrating that the patella (quadriceps) is denser than the calcaneus (Achilles). Additionally, no differences were observed in CSA between the 2 allografts before ($P = .54$) or after ($P = .93$) sizing, demonstrating that no bias was introduced during graft preparation. The Achilles allograft was significantly longer prior to sizing ($P = .00059$); however, after sizing, there was no difference between the length of the Achilles and quadriceps allografts ($P = .29$), confirming no bias between graft types due to preparation. No correlation ($R^2 < 0.2$ for all correlations) was found between structural properties during failure testing (maximum load and stiffness) and knee (age, BMI, and BMD) demographics. Low correlations were found between allograft age and failure stiffness ($R^2 = 0.291$) and between allograft length prior to sizing and maximum force ($R^2 = 0.221$). No correlation ($R^2 < 0.2$) was found between all other allograft (age, BMI, BMD, CSA, and length) demographics and structural properties during failure testing.

Cyclic Testing

Statistical differences were noted between the 2 neutral orientation cyclic regimens with respect to creep

TABLE 1
Group Specimen Demographics for Cadaveric Knees[a]

			Bone Mineral Density, HU		
	Age, y	BMI, kg/m^2	Femur	Medial Condyle	Tibia
PCL group, mean ± SD					
Intact	60.57 ± 8.38	20.54 ± 3.63	240.18 ± 55.34	366.93 ± 97.11	117.84 ± 50.47
Achilles	60.18 ± 7.68	27.37 ± 8.53	235.03 ± 72.61	369.26 ± 127.17	103.64 ± 50.41
Quadriceps	58.36 ± 7.27	26.92 ± 8.57	253.80 ± 54.34	376.52 ± 93.51	113.82 ± 44.58
ANOVA	0.23	1.96	0.26	0.02	0.22
P value	.80	.16	.77	.98	.80

[a]ANOVA, analysis of variance for intact vs Achilles vs quadriceps; BMI, body mass index; HU, Hounsfield units; PCL, posterior cruciate ligament.

TABLE 2
Group Specimen Demographics for Allografts[a]

			BMD, HU, Bone Block	CSA, mm^2		Length, mm	
	Age, y	BMI, kg/m^2		Before Sizing	After Sizing	Before Sizing	After Sizing
PCL group, mean ± SD							
Achilles	58.29 ± 8.30	30.95 ± 5.55	336.97 ± 144.92	145.89 ± 33.69	72.01 ± 14.08	20.79 ± 5.39	10.20 ± 2.51
Quadriceps	55.86 ± 9.01	30.37 ± 6.09	593.00 ± 208.73	161.59 ± 56.42	73.03 ± 24.86	10.05 ± 2.93	8.91 ± 1.85
t test	0.52	0.18	−3.34	−0.63	−0.09	4.63	1.10
P value	.61	.86	.0032	.54	.93	.00059	.29

[a]BMD, bone mineral density; BMI, body mass index; CSA, cross-sectional area; PCL, posterior cruciate ligament. Student *t* test for Achilles and quadriceps.

TABLE 3
Group Specimen Cyclic Testing Characterizations[a]

	P-V Extension, mm		Creep Deformation, mm	
	Neutral I	External Rotation	Neutral I	External Rotation
PCL group, mean ± SD				
Intact	1.75 ± 0.64	2.13 ± 0.63	0.77 ± 0.16	0.85 ± 0.34
Achilles	1.81 ± 0.44	2.70 ± 0.81	3.33 ± 0.91	3.14 ± 2.16
Quadriceps	1.78 ± 0.41	2.29 ± 0.76	3.52 ± 1.01	2.98 ± 1.06
ANOVA	0.03	1.38	26.11	5.95
P value	.97	.27	.0001	.0077
Tukey HSD post hoc	—	—	HSD[.05] = 0.98	HSD[.05] = 1.72
			HSD[.01] = 1.26	HSD[.01] = 2.22
			M1 vs M2, *P* < .01	M1 vs M2, *P* < .01
			M1 vs M3, *P* < .01	M1 vs M3, *P* < .05
			M2 vs M3, not significant	M2 vs M3, not significant

[a]ANOVA, analysis of variance for intact vs Achilles vs quadriceps; HSD, honestly significant difference; PCL, posterior cruciate ligament; P-V extension, peak minus valley of the last cycle to show stretch.

deformation for both the Achilles and quadriceps PCL reconstruction groups (repeated-measures ANOVA, Tukey post hoc test *P* < .05), where the second neutral cyclic regimen resulted in a decrease in creep deformation. This comparison suggests that over time allografts are affected by repeated testing, demonstrating less stretch during the last cyclic regimen as compared with the first. However, the overall conclusions between groups did not change whether the first or third regimen (neutral) was used for group comparisons.

Although repetitive cyclic testing likely had an effect on the external rotation cyclic regimen due to repeated testing,

properties of neutral or externally rotated regimens were only compared with themselves across the 3 specimen groups to ensure no bias. This would diminish partiality from repeated testing as each specimen was always tested in the same sequence. Therefore, for ease of explanation, only the first neutral and external regimens were used in subsequent analysis and result sections.

The intact PCL exhibited significantly lower creep deformation values than that of both the Achilles and quadriceps PCL reconstructions for both neutral I and external positions (*P* = .0001 and .0077), as seen in Table 3. However, no

TABLE 4
Achilles Versus Quadriceps Posterior Cruciate Ligament Reconstruction Cyclic Testing and Pull-to-Failure Comparisons[a]

	P-V Extension, mm		Creep Deformation, mm		Failure Testing	
	Neutral I	External Rotation	Neutral I	External Rotation	Max Load (N)	Stiffness (N/mm)
PCL group, mean ± SD						
Achilles	1.81 ± 0.44	2.70 ± 0.81	3.33 ± 0.91	3.14 ± 2.16	487.02 ± 148.07	42.80 ± 11.42
Quadriceps	1.78 ± 0.41	2.29 ± 0.76	3.52 ± 1.01	2.98 ± 1.06	616.19 ± 123.72	43.15 ± 7.16
t test	0.14811	1.1854	−0.46539	0.22421	−2.11697	−0.08203
P value	.88	.25	.65	.82	.048	.94

[a]PCL, posterior cruciate ligament; P-V extension, peak minus valley of the last cycle to show stretch. Student *t* test for Achilles and quadriceps.

TABLE 5
Group Specimen Pull-to-Failure Characterizations[a]

	Maximum Load, N	Load at 3 mm, N	Load at 5 mm, N	Stiffness, N/mm
PCL group, mean ± SD				
Intact	1974.88 ± 752.73	91.30 ± 82.77	198.00 ± 147.04	117.29 ± 8.90
Achilles	487.02 ± 148.07	7.58 ± 8.93	24.36 ± 25.58	42.80 ± 11.42
Quadriceps	616.19 ± 123.72	2.96 ± 7.74	9.47 ± 17.72	43.15 ± 7.16
ANOVA	34.02	10.90	14.83	162.87
P value	.0001	.00043	.0001	.0001
Tukey HSD post hoc	HSD[.05] = 471.15	HSD[.05] = 50.18	HSD[.05] = 90.71	HSD[.05] = 11.2
	HSD[.01] = 606.98	HSD[.01] = 64.64	HSD[.01] = 116.87	HSD[.01] = 14.43
	M1 vs M2, *P* < .01	M1 vs M2, *P* < .01	M1 vs M2, *P* < .01	M1 vs M2, *P* < .01
	M1 vs M3, *P* < .01	M1 vs M3, *P* < .01	M1 vs M3, *P* < .01	M1 vs M3, *P* < .01
	M2 vs M3, ns	M2 vs M3, ns	M2 vs M3, ns	M2 vs M3, ns

[a]ANOVA, analysis of variance for intact vs Achilles vs quadriceps; HSD, honestly significant difference; ns, not significant; PCL, posterior cruciate ligament.

significant difference was observed between the 2 PCL reconstruction graft types (Table 4).

For extension (P-V) stretch, the intact PCL and both PCL reconstructions exhibited similar results. There was no statistical difference at neutral I or external rotation for stretch among the 3 groups, as displayed in Table 3. In the quadriceps and Achilles subgroup analysis, there were no significant differences for extension (P-V) in both neutral I and external rotation as well as creep deformation, as displayed in Table 4.

Failure Testing

After 3 cycles of cyclic testing and rest, each specimen continued on to failure testing. One specimen from the Achilles cohort failed during cyclic testing during external rotation as the suture pulled through the bone plug and was subsequently excluded from failure testing. A total of 28 specimens reached the failure stage of testing. Representative force-extension curves obtained during the failure testing can be seen in Figure 1. The intact PCL specimens reached significantly (*P* = .0001) greater maximum loads compared with both the Achilles and quadriceps PCL reconstructions during pull-to-failure (intact PCL, 1974.88 ± 752.73 N; Achilles PCL reconstruction, 487.02 ± 148.07 N; quadriceps PCL reconstruction, 616.19 ± 123.72 N) (Table 5).

In comparing ultimate loads, the quadriceps PCL reconstruction had a significantly greater maximum load compared with the Achilles (*P* = .0485), as seen in Table 4. Stiffness values during pull-to-failure exhibited significantly greater results for the intact PCL at 117.29 ± 8.90 N/mm (*P* = .0001) compared with Achilles and quadriceps PCL reconstructions (42.80 ± 11.42 N/mm and 43.15 ± 7.16 N/mm); however, there were no differences seen between the 2 PCL reconstruction subtypes in Table 4. These failure results suggest that neither the Achilles nor quadriceps PCL reconstructions regain structural properties to that of the intact PCL after reconstruction. There was no statistical significance in failure properties between graft types for PCL reconstruction except for in maximum force where the quadriceps had a significantly greater force than the Achilles (*P* = .0485). The mechanism of failure for the intact PCL included tibial bone avulsions (n = 4), midsubstance ligamentous failure (n = 2), and ligamentous failure near the tibial insertion (n = 1). For Achilles tendon allograft reconstructions, the mechanism of failure included stretch/slippage on the femoral side (n = 5), bone plug failure (n = 2), graft sheering on the tibial side (n = 2), tibial screw subsidence (n = 1), and failure at the tendon-osseous junction (n = 1). For quadriceps tendon allograft reconstructions, the mechanism of failure
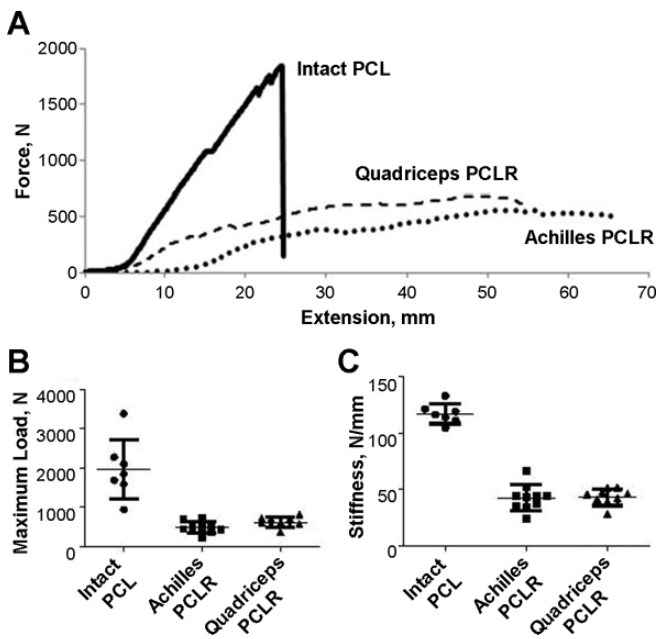
Figure 1. (A) Representative force-extension curves for the intact posterior cruciate ligament (PCL) and allograft PCL reconstruction (PCLR) groups. Structural properties for each group including (B) maximum force and (C) stiffness are reported as individual data points, with bars representing mean ± SD (n = 11 per group).

included stretch/slippage on the femoral side (n = 4), graft stretch/sheering on the tibial side (n = 3), failure at tendon-osseous junction (n = 2), tibial plateau bone failure (n = 1), and midsubstance graft failure (n = 1).

The most common mechanism of failure in the PCL reconstruction groups was via graft slippage and displacement from the femoral tunnel. Our study therefore partially evaluated the fixation strength at the femur for these specimens during failure testing alongside the graft properties of the remaining specimens. After eliminating specimens that failed via fixation on the femoral or tibial side, analysis revealed that the quadriceps group failed at a greater maximum load (604.66 ± 68.39 vs 454.78 ± 211.504 N for Achilles), though results were not statistically significant ($P = .174$) with the small number of specimens available for analysis. Additionally, the quadriceps group trended toward a stiffer construct (42.39 ± 5.46 vs 37.62 ± 9.15), with no significant differences noted ($P = .36$).

DISCUSSION

The primary findings of this study were that the failure characteristics of the 2 grafts (quadriceps vs Achilles) were generally similar to one another but significantly less than the native PCL, with failure consistently noted on the femoral side for reconstructions. The quadriceps tendon construct had a significantly greater load to failure than the Achilles tendon construct, despite similar CSAs. While our maximal load to failure is similar to that of other biomechanical studies evaluating PCL reconstructions,[12] the

weak link of the reconstruction appears to be at the level of the femoral fixation.

Recent studies have indicated that typical improvement of one grade of stability is achieved with PCL reconstruction.[21] The most common PCL reconstruction technique currently employed is a transtibial technique with an Achilles tendon allograft; however, this is a point of significant debate. Several studies have recommended a tibial inlay, arthroscopic or open, to decrease the risk of a "killer turn" that is often seen with arthroscopic PCL reconstruction.[11,19,20,28] While the type of tibial fixation is debatable, for this study, we chose the most common method of PCL reconstruction.

The PCL has a larger CSA, a larger native footprint, and greater stiffness than the ACL.[17] Therefore, to have an anatomic PCL reconstruction, intuitively a larger graft would be needed. Both Achilles and quadriceps tendon allografts have a greater cylindrical area than that of a patellar bone–tendon-bone graft, which may better replicate the larger size of the PCL.[17] Achilles tendon allografts have been an attractive option for PCL reconstructions as they are readily available from most tissue banks and they have a long tendinous portion with an attached bone block providing a suitable point of fixation. It is a versatile graft that can be configured into both single- and double-stranded constructs. The quadriceps tendon, on the other hand, is an increasingly more common graft choice for ACL reconstructions as it also provides a large soft tissue graft that is better able to fill the native footprint and replicate the larger size of the native ACL.[18,32] It has been shown to be very successful in ACL reconstructions but has not been extensively studied with PCL reconstructions.[34] The quadriceps tendon, like the Achilles tendon, also provides the option to use a bone plug to improve the security of graft fixation and to allow for early osseous healing. The quadriceps tendon is bifid by nature due to the rectus femoris and vastus intermedius insertion, allowing for use if a double-bundle PCL reconstruction is desired. All these factors make the quadriceps tendon allograft an attractive option for PCL reconstructions.

Several clinical studies on PCL reconstructions have shown good results with Achilles tendon allografts,[2,22,29] while only a few studies have described the results of quadriceps tendon autografts in PCL reconstructions.[1,6,9,25,27,34] Limited biomechanical testing has been performed on quadriceps tendon grafts,[24,32] and no study to our knowledge has shown any biomechanical or outcomes data for PCL reconstructions with quadriceps allograft tendons. A recent study by Mabe and Hunter[24] biomechanically compared quadriceps tendon allografts with Achilles tendon allografts in isolation to determine whether the quadriceps might be a viable alternative in reconstructive procedures. The quadriceps demonstrated a range of maximum load to failure of 1055 ± 313 N, and the Achilles failed at 915 ± 326 N. With cyclic testing, both the quadriceps and Achilles tendons had similar elongations of 1.97% and 1.24%, respectively. In 6 of 8 parameters tested, the Achilles and quadriceps tendons were found to be equivalent. Staubli et al[32] demonstrated that the mean CSA of a 10-mm-wide quadriceps tendon graft is on average 64.4 ± 18.4 mm^2 and has a load to failure of 2172 ± 618 N. In our study, both the Achilles and quadriceps tendon allografts had similar CSAs.

Similar to previous studies,[21] we found that neither Achilles nor quadriceps tendon allografts were able to restore native ligament stability or stiffness. The intact PCL exhibited significantly lower creep deformation than both the Achilles and quadriceps tendon allografts in both neutral and external rotation, as well as a trend of lower extension during cyclic regimens. The stiffness during pull to failure was also significantly better for the intact PCL than for either reconstruction techniques, as was the load to failure.

The load to failure of our Achilles and quadriceps reconstructions were both comparable to previously reported values for PCL reconstructions.[12] In the study by Mabe and Hunter,[24] where the grafts where tested in isolation, the load to failure of both graft types was closer to that of the intact PCL in our study. In their study, the grafts often failed at the bone-tendon junction for the Achilles and at the midsubstance in the quadriceps tendon allografts. In our study, the most common mode of failure with either graft was at the level of the femoral fixation, despite utilization of a post as well as an interference screw. While our maximal load to failure is similar to that of other biomechanical studies evaluating PCL reconstructions,[12] the weak link of the reconstruction appears to be at the level of the femoral fixation. Such results are encouraging as the graft strength of both the Achilles and quadriceps tendon allografts did not seem to be the limiting factor.

The BMD of the patella was significantly greater than that of the calcaneus. Intuitively one would think that the increased bony density might aid in fixation strength of the bone block with an interference screw and that the Achilles would fail at lower levels than the quadriceps tendon graft. That was not demonstrated in our study as failure occurred at the level of femoral fixation.

Limitations in this study include the fact that only a transtibial single-bundle reconstruction was chosen. This was performed to verify that the quadriceps tendon allograft would be a viable graft alternative to Achilles tendon allografts, but other studies have shown that tibial inlay and double-bundle reconstructions may have better biomechanical characteristics than a single-bundle transtibial technique.[7-9,11,16,22,26,33] Future studies may be performed to evaluate and optimize surgical techniques with the quadriceps tendon allografts. Second, the load deformation curves for both PCL reconstruction groups do not show a truly linear relationship, therefore limiting our calculation of stiffness. Despite this limitation, we were able to show significant differences between intact PCL and PCL reconstruction groups. Third, this time-zero biomechanical study does not allow for the integration of the tendon–bone block allograft into the femoral and tibial tunnels. This, in part, may account for differences between reconstructed groups and the native, intact PCL groups. This initial construct weakness may improve with graft integration over the initial 3 to 4 months. Finally, the most common mechanism of failure in the reconstruction groups was at the level of fixation on the femoral side, despite being fixed with interference screws and backed up with a suture tied over a post. Future studies may employ larger interference screws or alternative suture material to facilitate stronger fixation.

CONCLUSION

PCL reconstructions with either Achilles tendon allograft or quadriceps tendon allograft were able to reproduce native PCL biomechanical strength. Among the reconstructed PCL groups, the quadriceps group had a significantly greater load to failure. The most common mechanism of failure was via graft fixation on the femoral side. Currently, quadriceps tendon allografts are not widely used for PCL reconstructive procedures. This study demonstrates that quadriceps tendon allografts are biomechanically equivalent to the current most commonly used graft, an Achilles allograft, which increases the overall allograft availability options for PCL reconstruction.

ACKNOWLEDGMENT

REFERENCES

1. Aglietti P, Buzzi R, Lazzara D. Posterior cruciate ligament reconstruction with the quadriceps tendon in chronic injuries. *Knee Surg Sports Traumatol Arthrosc.* 2002;10:266-273.
2. Ahn JH, Yoo JC, Wang JH. Posterior cruciate ligament reconstruction: double-loop hamstring tendon autograft versus Achilles tendon allograft—clinical results of a minimum 2-year follow-up. *Arthroscopy.* 2005;21:965-969.
3. Barrett GR, Savoie FH. Operative management of acute PCL injuries with associated pathology: long-term results. *Orthopedics.* 1991;14:687-692.
4. Boynton MD, Tietjens BR. Long-term followup of the untreated isolated posterior cruciate ligament-deficient knee. *Am J Sports Med.* 1996;24:306-310.
5. Chen CH, Chen WJ, Shih CH. Arthroscopic reconstruction of the posterior cruciate ligament: a comparison of quadriceps tendon autograft and quadruple hamstring tendon graft. *Arthroscopy.* 2002;18:603-612.
6. Chen CH, Chen WJ, Shih CH, Chou SW. Arthroscopic posterior cruciate ligament reconstruction with quadriceps tendon autograft: minimal 3 years follow-up. *Am J Sports Med.* 2004;32:361-368.
7. Chhabra A, Kline AJ, Harner CD. Single-bundle versus double-bundle posterior cruciate ligament reconstruction: scientific rationale and surgical technique. *Instr Course Lect.* 2006;55:497-507.
8. Chuang TY, Chen CH, Chou SW, Chen YJ, Chen WJ. Tibial inlay technique with quadriceps tendon-bone autograft for posterior cruciate ligament reconstruction. *Arthroscopy.* 2004;20:331-335.
9. Chuang TY, Ho WP, Chen CH, Liao YS, Chen WJ. Double-bundle posterior cruciate ligament reconstruction using inlay technique with quadriceps tendon-bone autograft. *Arthroscopy.* 2004;20:e23-e28.
10. Clancy WG Jr, Shelbourne KD, Zoellner GB, Keene JS, Reider B, Rosenberg TD. Treatment of knee joint instability secondary to rupture of the posterior cruciate ligament. Report of a new procedure. *J Bone Joint Surg Am.* 1983;65:310-322.
11. Cooper DE, Stewart D. Posterior cruciate ligament reconstruction using single-bundle patella tendon graft with tibial inlay fixation: 2- to 10-year follow-up. *Am J Sports Med.* 2004;32:346-360.
12. Ettinger M, Wehrhahn T, Petri M, et al. The fixation strength of tibial PCL press-fit reconstructions. *Knee Surg Sports Traumatol Arthrosc.* 2012;20:308-314.
13. Forsythe B, Harner C, Martins CA, Shen W, Lopes OV Jr, Fu FH. Topography of the femoral attachment of the posterior cruciate ligament. Surgical technique. *J Bone Joint Surg Am.* 2009;91(suppl 2 pt 1):89-100.

14. Fulkerson JP, Langeland R. An alternative cruciate reconstruction graft: the central quadriceps tendon. *Arthroscopy*. 1995;11:252-254.

15. Harner CD, Hoher J. Evaluation and treatment of posterior cruciate ligament injuries. *Am J Sports Med*. 1998;26:471-482.

16. Harner CD, Janaushek MA, Kanamori A, Yagi M, Vogrin TM, Woo SL. Biomechanical analysis of a double-bundle posterior cruciate ligament reconstruction. *Am J Sports Med*. 2000;28:144-151.

17. Harner CD, Xerogeanes JW, Livesay GA, et al. The human posterior cruciate ligament complex: an interdisciplinary study. Ligament morphology and biomechanical evaluation. *Am J Sports Med*. 1995;23:736-745.

18. Hoher J, Scheffler S, Weiler A. Graft choice and graft fixation in PCL reconstruction. *Knee Surg Sports Traumatol Arthrosc*. 2003;11:297-306.

19. Huang TW, Wang CJ, Weng LH, Chan YS. Reducing the "killer turn" in posterior cruciate ligament reconstruction. *Arthroscopy*. 2003;19:712-716.

20. Kim SJ, Choi CH, Kim HS. Arthroscopic posterior cruciate ligament tibial inlay reconstruction. *Arthroscopy*. 2004;20(suppl 2):149-154.

21. Kim YM, Lee CA, Matava MJ. Clinical results of arthroscopic single-bundle transtibial posterior cruciate ligament reconstruction: a systematic review. *Am J Sports Med*. 2011;39:425-434.

22. Lim HC, Bae JH, Wang JH, et al. Double-bundle PCL reconstruction using tibial double cross-pin fixation. *Knee Surg Sports Traumatol Arthrosc*. 2010;18:117-122.

23. Lipscomb AB Jr, Anderson AF, Norwig ED, Hovis WD, Brown DL. Isolated posterior cruciate ligament reconstruction. Long-term results. *Am J Sports Med*. 1993;21:490-496.

24. Mabe I, Hunter S. Quadriceps tendon allografts as an alternative to Achilles tendon allografts: a biomechanical comparison. *Cell Tissue Bank*. 2014;15:523-529.

25. Mariani PP, Margheritini F. Full arthroscopic inlay reconstruction of posterior cruciate ligament. *Knee Surg Sports Traumatol Arthrosc*. 2006;14:1038-1044.

26. Race A, Amis AA. The mechanical properties of the two bundles of the human posterior cruciate ligament. *J Biomech*. 1994;27:13-24.

27. Richards RS, Moorman CT. Use of autograft quadriceps tendon for double-bundle posterior cruciate ligament reconstruction. *Arthroscopy*. 2003;19:906-915.

28. Salata MJ, Sekiya JK. Arthroscopic posterior cruciate ligament tibial inlay reconstruction: a surgical technique that may influence rehabilitation. *Sports Health*. 2011;3:52-58.

29. Sekiya JK, West RV, Ong BC, Irrgang JJ, Fu FH, Harner CD. Clinical outcomes after isolated arthroscopic single-bundle posterior cruciate ligament reconstruction. *Arthroscopy*. 2005;21:1042-1050.

30. Shelbourne KD, Davis TJ, Patel DV. The natural history of acute, isolated, nonoperatively treated posterior cruciate ligament injuries. A prospective study. *Am J Sports Med*. 1999;27:276-283.

31. Shelbourne KD, Haro MS, Gray T. Knee dislocation with lateral side injury: results of an en masse surgical repair technique of the lateral side. *Am J Sports Med*. 2007;35:1105-1116.

32. Staubli HU, Schatzmann L, Brunner P, Rincon L, Nolte LP. Mechanical tensile properties of the quadriceps tendon and patellar ligament in young adults. *Am J Sports Med*. 1999;27:27-34.

33. Whiddon DR, Zehms CT, Miller MD, Quinby JS, Montgomery SL, Sekiya JK. Double compared with single-bundle open inlay posterior cruciate ligament reconstruction in a cadaver model. *J Bone Joint Surg Am*. 2008;90:1820-1829.

34. Wu CH, Chen AC, Yuan LJ, et al. Arthroscopic reconstruction of the posterior cruciate ligament by using a quadriceps tendon autograft: a minimum 5-year follow-up. *Arthroscopy*. 2007;23:420-427.